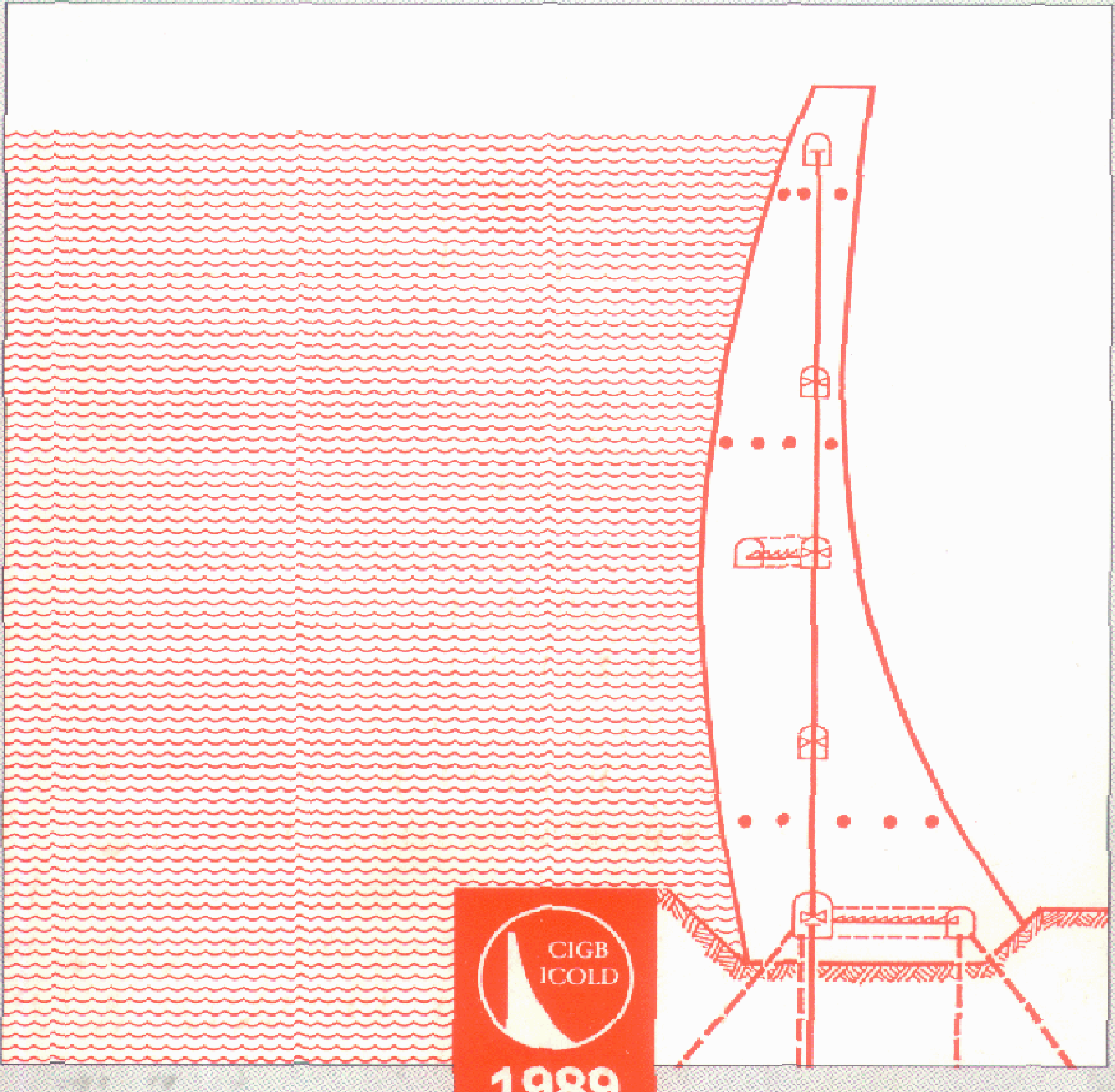
MONITORING OF DAMS AND THEIR FOUNDATIONS.

State of the art.

AUSCULTATION DES BARRAGES ET DE LEURS FONDATIONS.

La technique actuelle.

Bulletin 68



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AVANT-PROPOS

Le Comité de l'Auscultation des Barrages et de leurs Fondations a été constitué à Rio de Janeiro, en 1982, lors de la cinquantième Réunion Exécutive de la CIGB.

Les missions confiées au Comité étaient les suivantes :

a) mettre à jour et fondre en un fascicule unique les Bulletins 21 et 23;

b) faire l'inventaire des méthodes de surveillance, illustrer les expériences acquises, présenter les nouveaux appareils;

c) illustrer les méthodes de surveillance continue et les méthodes d'élaboration et d'interprétation des résultats;

d) décrire les méthodes d'auscultation sismique des barrages;

e) illustrer les possibilités d'automatisation de la surveillance;

f) étudier les problèmes des vieux barrages.

Chaque pays membre du Comité a été prié d'établir un rapport sur la technique actuelle dans son pays en ce qui concerne l'auscultation des barrages et de leurs fondations. Dix rapports furent ainsi présentés, plus un onzième, établi par le Canada qui n'était pas membre du Comité.

Devant la difficulté de faire une synthèse complète de ces rapports sans perdre certaines informations du plus haut intérêt, il fut décidé qu'ils formeraient le corps même du rapport du Comité et qu'ils seraient précédés d'une Note de Synthèse. On s'est efforcé dans celle-ci de regrouper, en dix rubriques, les observations présentées, le plan étant d'ailleurs celui qui avait été suggéré aux Comités Nationaux pour leur contribution. Sans être exhaustive, cette Note de Synthèse permettra au lecteur d'identifier les contributions qui traitent de sujets l'intéressant.

Dans son rapport, chaque pays a insisté naturellement davantage sur les activités auxquelles il attache le plus d'importance ou sur celles qui sont à la pointe de la technique. Parmi les différentes situations exposées, le lecteur pourra donc choisir celle qui correspond le mieux à ses préoccupations et en tirer d'utiles enseignements, tout en sachant que ces contributions traitent de solutions réelles, mises en œuvre par des techniciens qualifiés.

Les principes de base d'une auscultation correcte sont décrits dans le Bulletin 60, publié en 1988 : c'est une mise à jour des Bulletins 21 et 23 de 1969 et 1972, avec refonte en un seul fascicule. Ce Bulletin 60 peut donc être considéré comme une introduction générale au présent Bulletin.

Que tous les membres du Comité, dont l'expérience et le dévouement ont permis l'établissement de ce rapport, trouvent ici l'expression de mes remerciements.

Alfredo MARAZIO
Président du Comité de l'Auscultation
des Barrages et de leurs Fondations

FOREWORD

The Committee on Monitoring of Dams and their Foundations was established in Rio de Janeiro, in April 1982, at the 50th Executive Meeting of ICOLD.

The Committee's terms of reference were as follows :

a) update, revise and integrate ICOLD Bulletins Nos. 21 and 23 into a single ICOLD Bulletin;

b) make an inventory of the dam surveillance methods, illustrate experience acquired, and present information on new equipment;

c) illustrate methods of continuous surveillance of dams and procedures for data processing and interpretation;

d) describe seismic monitoring methods for dams;

e) illustrate the possibilities of automated surveillance;

f) study the problems of older dams.

The member countries of the Committee were asked to submit state-of-the-art reports on dam and foundation monitoring in their own countries, and ten reports were finally forthcoming. Canada, not a member of the Committee, also furnished a report.

It was considered impossible to digest all these contributions into a single report without losing some highly useful information, and it was therefore decided that they would form the body of the Committee's report and that they would be preceded by an Overview. The latter would attempt to classify the information under ten headings, following the same plan as was suggested for the National contributions. It is not an exhaustive compilation but will help the reader to identify the contributions dealing with problems of interest to him.

Understandably, each contribution has highlighted those activities that are considered to be either the most important in the country or technically the most advanced. From the different situations, the reader may therefore choose the one that best meets his own situation and draw useful guidance from it, knowing that what is described represents actual situations developed by technical experts in this field.

The basic principles of good monitoring practice are described in Bulletin 60, published in 1988, itself an updating of earlier Bulletins 21 and 23 issued in 1969 and 1972, merged in a single brochure. Bulletin 60 can therefore be considered as a general introduction to this report.

I wish to extend my thanks to all members who have contributed their time and experience and made the accomplishment of this task possible.

Alfredo MARAZIO
Chairman, Committee on Monitoring of
Dams and their Foundations

NOTE DE SYNTHÈSE

1. SÉCURITÉ DES BARRAGES

Dans la plupart des rapports, on traite, en première partie, des problèmes généraux de sûreté des barrages et des liens qui existent entre sûreté et auscultation de l'ouvrage.

On admet généralement que la sûreté d'un ouvrage ne dépend pas seulement d'une bonne conception et d'une exécution correcte, mais aussi de la surveillance de son comportement pendant les premières années d'exploitation et toute la durée de vie de l'ouvrage. De plus, une auscultation adéquate permet d'obtenir des informations qui enrichissent nos connaissances sur le comportement réel des ouvrages et donne, en fin de compte, l'occasion d'affiner nos techniques expérimentales et nos méthodes de calcul en vue d'une conception meilleure et plus sûre des futurs barrages.

Le rapport du Comité Français décrit l'organisation, à l'échelle nationale — celle mise en place par EDF — d'un système d'auscultation qui vise à une surveillance efficace et homogène. Le rapport insiste sur la législation en vigueur en France : l'auscultation et la surveillance incombent au maître d'ouvrage (propriétaire); le Service de l'État chargé du contrôle vérifie que la surveillance est convenablement assurée par le maître d'ouvrage.

Le rapport du Comité Autrichien souligne le rôle de l'exploitant de barrage dont la tâche est d'assurer une maintenance convenable du dispositif de mesure, de vérifier la validité des lectures, d'informer les autorités de tout événement extraordinaire pouvant survenir et finalement d'alerter les populations si nécessaire.

Le rapport du Comité Italien considère essentiel, pour émettre une estimation de la sécurité d'un barrage, de comparer les mesures faites *in situ* avec les prévisions correspondantes provenant des modèles de référence qui sont, soit du type simple, comme les systèmes statiques, soit d'un type plus complexe, comme les systèmes déterministes ou mixtes (hybrides). C'est seulement de cette façon que l'estimation de la sûreté peut être considérée comme objective, rationnelle et rapide.

Le rapport du Comité Japonais insiste sur l'idée que l'estimation de la sûreté, dans le cas d'un barrage particulier, doit prendre en compte les conditions spéciales auxquelles est soumis ce barrage. Dans l'étude finale, la fiabilité de l'estimation elle-même est basée, pour chaque barrage, sur la disponibilité d'une banque de données correctes fournies par une auscultation systématique de l'ouvrage. De plus, compte tenu du fait que le Japon est un pays particulièrement sismique, une grande importance est accordée à la sécurité vis-à-vis des séismes et, par conséquent, à l'auscultation sismique de tels ouvrages.

Le rapport du Comité Sud-Africain insiste fortement sur les particularités géographiques et démographiques du pays, par exemple les grandes distances entre barrages — ce qui nécessite un personnel décentralisé et logé sur le site de l'ouvrage —, les conditions climatiques spécialement favorables pour accéder aux barrages toute l'année et finalement, dans de nombreux cas, l'absence de centres urbains à l'aval des ouvrages.

OVERVIEW

1. DAM SAFETY

In most of the reports, the first part deals with the general problems of dam safety and the relationship between safety and monitoring.

It is generally accepted that safety does not depend only on proper design and construction, but also on monitoring actual behaviour during the first few years of operation and over the service life of the structure. Furthermore, proper monitoring offers the possibility of obtaining information that aids in enhancing our knowledge of actual behaviour, and therefore also offers the opportunity of refinements in analytical and experimental techniques for better and safer designs for future dams.

In this context, the French report puts particular stress on the national dam monitoring organization designed to achieve effective consistent control. A detailed description is provided of the organization headed by EdF. The report describes legislation in France : dam monitoring and inspection is the responsibility of the owner; the Regulatory Authority ensures correct surveillance by the owner.

The Austrian report emphasizes the role of the dam operator whose task it is to ensure suitable maintenance of the instrument system, check the validity of readings, inform the authorities of the occurrence of extraordinary events, and finally, to warn the population when necessary.

The Italian report deems it essential for dam safety evaluation to compare instrumental data with forecasts from simple models (e.g. statistical) or more complex types (deterministic or mixed-hybrid-models). Only in this manner can the evaluation be objective, rational and rapid.

The Japanese report stresses the concept that the safety evaluation for a particular dam has to take into account the special conditions that the dam is subjected to. In the final analysis, the reliability of the evaluation is dependent on the availability of a sound data bank obtained through systematic monitoring of the structure. Since Japan is a particularly seismic country, greater weight is given to the seismic safety of dams and consequently to their seismic monitoring.

The South African report strongly emphasizes consideration of the particular geographical and demographic situation of the country. These include : large distances between one dam and another, thus requiring personnel to be decentralized and located on the site of the structure; climatic conditions especially favourable for access to the dams throughout the year; and finally in many cases the absence of population centers downstream of the dams.

Le rapport du Comité Suisse exprime l'idée que la sûreté d'un barrage est essentiellement basée sur le contrôle de qualité de la construction, sur des observations visuelles et sur un contrôle du comportement de l'ouvrage au moyen d'appareils appropriés, ainsi que sur une analyse et une interprétation rapides des résultats de mesures obtenus. De plus, dans le cas d'événements extraordinaires, il est important d'avoir prévu une stratégie et une organisation adéquates pour parer au mieux au danger, en décidant à l'avance quel est le personnel responsable et où se trouvent les centres de décision. A ce sujet, un rôle fondamental est joué par le gardien du barrage qui constitue le premier témoin capable de se rendre compte d'un événement inhabituel et d'en faire part.

Le rapport du Comité Norvégien rappelle les conditions topographiques et géologiques de son pays. Celles-ci sont hautement favorables aux barrages en terre et ont conduit à des ouvrages dont, le plus souvent, la conception et la construction se ressemblent, ce qui a permis d'éviter une auscultation extensive dans la plupart d'entre eux. Cependant, un dispositif complet d'auscultation est installé sur ceux d'entre eux qui présentent un comportement inhabituel ou qui sont les premiers d'une nouvelle série.

Le rapport du Comité des États-Unis souligne le fait que des accidents sérieux peuvent survenir, même aujourd'hui, et sont d'ailleurs survenus, et que cette constatation rend la surveillance des barrages impérative pour prévoir et prévenir de telles catastrophes. Ces accidents peuvent se produire plus ou moins rapidement, parfois même après plusieurs années d'exploitation; on ne peut alors les détecter que par une auscultation très soigneuse de chaque ouvrage.

Dans le rapport du Comité Australien, on insiste sur l'importance de l'auscultation pour la sûreté des barrages, spécialement dans le cas de vieux barrages, où les appareils de mesure sont capables de fournir des informations sur la façon dont l'ouvrage satisfait aux critères les plus courants de sécurité. De plus, la complexité et l'étendue d'un dispositif de mesure dans le cas d'un barrage particulier dépend aussi de l'importance socio-économique du barrage lui-même, de même que du degré de danger qu'il représente pour les populations en aval.

Le rapport du Comité Portugais relève le fait que les maîtres d'ouvrages devraient être — ou sont — bien avertis que le coût d'une auscultation appropriée est d'un ordre de grandeur très différent du montant des dommages qui pourraient survenir en cas d'accident.

Le rapport du Comité Canadien rappelle que l'auscultation en elle-même ne rend pas un barrage plus sûr; sa sûreté ne repose réellement que sur sa conception et sa construction. Les appareils de mesure donneront des informations sur la façon dont le barrage se comporte pour permettre, si nécessaire, une intervention en vue d'éviter de sérieux dégâts.

2. GRANDEURS PHYSIQUES A MESURER ET APPAREILS DE MESURE

Tout en soulignant le rôle des Bulletins 21 et 23, ou plutôt du Bulletin 60 qui en constitue une mise à jour, on peut dire que tous les rapports s'accordent sur les grandeurs physiques à mesurer pour déterminer les performances d'un barrage.

The Swiss report expresses the view that the safety of a dam is essentially governed by proper construction control, visual inspection and performance monitoring by means of suitable instrumentation, rapid analysis, and interpretation of readings. For extraordinary events, it is important to have prepared a clearly-defined emergency plan to counter damage, having previously decided who are the staff responsible and where are the centers of decision. Within this framework, the fundamental role is assigned to the dam keeper, who is the first to identify and notify an unusual event.

The Norwegian report emphasizes the particular topographic and geologic conditions of the country. These are highly favourable for earth dams and have led to usually similar designs and construction. This common denominator has made it possible to avoid extensive instrumentation at most dams. However, a complete monitoring system is installed on those dams that exhibit unusual behaviour or that are the first of a new constructional type.

The United States report points to the fact that serious accidents can happen, and have happened, even today, and this fact makes dam surveillance imperative so as to be able to foresee and prevent such catastrophes. These accidents may develop more or less rapidly and can show up even after several years of operation, and can therefore be traced only by means of careful monitoring of each structure.

In the Australian report, the importance of monitoring in relation to dam safety is emphasized, especially in the case of older dams, where the instrumentation is capable of providing information on the adequacy of the structure in accord with the most current safety criteria. The complexity and completeness of the monitoring system of a particular dam also depends on the socio-economic importance of the dam itself, as well as on the degree of danger (hazard) it represents to population downstream.

The Portuguese report stresses the fact that owners of dams should be — or are — well aware that the cost of adequate monitoring is of a very different order from what would have to be borne in the case of an accident.

The Canadian report emphasizes that instrumentation in itself does not make a dam any safer; its safety really lies in the design and construction. Instrumentation will provide information on how the dam is behaving to allow intervention, if required, to avoid any serious damage.

2. PHYSICAL QUANTITIES AND RELATED INSTRUMENTATION

Besides reiterating the usefulness of Bulletins 21 and 23 (or their updated versions : Bulletin 60), it can be stated that almost all the contributions (reports) identify the same physical quantities that are useful for the purposes of monitoring dam performance.

Dans le rapport Italien, on distingue les grandeurs causales (celles par lesquelles l'environnement agit sur l'ouvrage) et les grandeurs résultantes (celles qui expriment la réponse de l'ouvrage aux variations du milieu).

Dans d'autres rapports, le Rapport Suisse par exemple, une distinction est faite entre les grandeurs à mesurer pour vérifier le comportement de l'ouvrage et celles qui sont plus spécialement utiles à la recherche en vue d'augmenter nos connaissances pour une meilleure conception des projets. Le rapport Autrichien indique clairement que les grandeurs les plus importantes et les plus significatives pour la sécurité d'un barrage sont les fuites et suintements et aussi les déplacements dans le cas de barrages-voûtes.

Finalement, dans tous les rapports, on souligne le rôle irremplaçable de l'observation visuelle. Pour quelques pays, tels l'Autriche, l'Italie, le Japon, le Portugal, le Canada, les États-Unis, l'observation visuelle est un complément utile et nécessaire à toutes les séries de mesures qu'il est possible de faire, même automatiquement.

Pour d'autres pays, dont l'Australie, la France, la Norvège, l'Afrique du Sud et la Suisse, l'observation visuelle est très sûre et permet fréquemment de détecter des anomalies qu'il serait impossible de mettre en évidence avec des instruments de mesure : fissures, fuites, dégradations locales, existence de taches d'humidité, etc.

De nombreux rapports soulignent l'importance de la charge thermique dans le cas des barrages en béton et le besoin qui en résulte de mesurer les températures à la fois du milieu ambiant et du béton. Ceci représente certainement un pas en avant vers la compréhension du comportement réel des barrages, alors que, jusqu'à présent, on admettait que la charge thermique était négligeable dans la plupart des cas.

Il y a un accord général sur les caractéristiques des instruments. Ils doivent être robustes, fiables, simples d'entretien et d'une lecture facile. Pour certains pays, tels que l'Autriche, l'Italie, le Canada et les États-Unis, il est important d'avoir aujourd'hui la possibilité de rendre ces capteurs automatiques et d'avoir ainsi la possibilité d'effectuer des auto-tests sûrs. Tout le monde est d'accord sur l'importance du pendule, direct ou inversé : c'est l'exemple d'un instrument simple et précis et d'une automatisation facile.

3. DISPOSITIFS DE MESURE

En ce qui concerne les dispositifs de mesure, il existe parmi les différents pays des différences significatives en ce qui concerne l'approche des mesures topographiques ou, plus généralement, des méthodes géodésiques.

La Suisse attribue une grande importance aux mesures géodésiques, qu'elle considère comme un dispositif de contrôle complémentaire en cas d'événement extraordinaire. Le principe consiste à établir un système tridimensionnel pour la mesure des déplacements du barrage et de ses fondations, consistant en un réseau horizontal (triangulation, polygonales) raccordé à un réseau vertical (pendules, nivellement).

L'Afrique du Sud et le Portugal considèrent que ces méthodes sont encore valables et utilisables dans certains cas, tandis que d'autres pays considèrent que ces

In the Italian report, they are subdivided into cause quantities (quantities by means of which the environment acts on the structure) and effect quantities (quantities that express the response of the structure to the environmental variations).

In other reports (the Swiss report, for example), a distinction is made between the quantities to be measured for purpose of checking the behaviour of the structure and those especially useful for research with a view to acquiring better knowledge, and thus aimed at future projects. The Austrian report clearly states that the most important and significant quantities in terms of dam safety are seepage losses and infiltrations, and also displacements of arch dams.

Finally, in all the reports, visual inspection is emphasized as being indispensable. For some of the countries, which include Austria, Italy, Japan, Portugal, Canada and United States, it is a useful and necessary complement to an entire series of measurements that can possibly be made, even automatically.

For other countries which include Australia, France, Norway, South Africa and Switzerland, visual inspection is very reliable and frequently it can detect anomalies that it is impossible to detect with instrumentation : cracks, water seepage losses, local material degradation, extension of wet spots, etc.

Quite a number of reports highlight the importance of the thermal load, especially in the case of concrete dams, and accordingly the need to measure temperatures of both the environment and the concrete. This certainly represents a step forward in the understanding of the actual behaviour of dams, in contrast to normal practice so far, that deemed the thermal load was negligible in most cases.

There is general agreement on the specifications for the instruments. They should be rugged, reliable, simple to maintain and easy to use. For some of the countries, such as Austria, Italy, Canada and United States, an important requisite today is the possibility of making the sensors automatic with the possibility of effecting reliable auto-tests. All parties agree on the importance of the pendulum, both direct and inverted, as an example of an accurate and simple instrument that can be automated.

3. MONITORING SYSTEMS

In regard to the monitoring systems, there is among the various countries a significant difference in approach to topographical survey or, more generally, geodetic methods.

Switzerland attaches much importance to geodetic measurements, regarded as a complementary control tool when extraordinary events happen. The methodology consists in establishing a tridimensional system to measure displacements of the dam and its foundations. This method is based on a horizontal network (triangulation, polygonals) connected to a vertical network (pendulums, levelling).

South Africa and Portugal still view this method as valid and feasible in certain cases, while other countries consider it partly obsolete, but sometimes employ it only procédés sont partiellement obsolètes et ne les utilisent quelquefois que pour la vérification des déplacements absolus d'un barrage, de sa fondation et des rives de la retenue.

Ce qu'on entend par « méthodes géodésiques » n'est pas toujours très clair. Si, par méthodes géodésiques, on désigne les méthodes qui prennent comme référence le champ gravitationnel (la direction de la verticale du lieu), alors beaucoup de ces méthodes sont encore valables, telles que les pendules, les clinomètres, les nivellements géométriques utilisés encore avec succès. Si, au contraire, le mot géodésique est réservé au nivellement trigonométrique, à la triangulation et aux intersections, alors l'opinion exprimée ci-dessus et indiquant que ces mesures sont de moins en moins utilisées est en gros valable.

Le rapport des États-Unis signale la possibilité d'employer les satellites pour l'auscultation géodésique. Cependant, cette technique, déjà utilisée pour un grand nombre de barrages aux États-Unis, nécessite un développement technique substantiel qui n'est peut-être pas à la portée de tous les pays.

Tout en signalant qu'il n'est pas toujours possible de parler d'un système de mesures en termes généraux, le rapport Sud-Africain souligne le besoin de réexaminer tous les barrages sur une base uniforme en s'appuyant sur les suggestions mentionnées dans le Bulletin n° 41 (1) de la CIGB et en les équipant avec de nouveaux instruments.

Le rapport Autrichien exprime la conviction qu'un système de mesures approprié permettrait de contrôler l'ensemble du barrage sans entraîner pour autant des coûts prohibitifs, par exemple, dans le cas d'un barrage-poids non clavé, en équipant un plot d'un dispositif complet de mesures et les autres plots de quelques instruments seulement pour permettre d'étendre les mesures du plot de référence à l'ensemble du barrage. Un exemple est donné pour illustrer plus en détail ce principe.

Le rapport des États-Unis donne une description très détaillée de toutes les études nécessaires pour concevoir correctement un dispositif de mesures.

Les rapports Norvégien et Australien fournissent une brève description non seulement des appareils utilisés mais aussi de leur installation et de leur procédé de lecture.

Les rapports Italien et Japonais soulignent qu'un dispositif d'auscultation est un système intégré qui comporte les aspects suivants :

a) les éléments qui caractérisent la sécurité du barrage et de sa fondation;

b) les grandeurs qui déterminent ou décrivent le mieux le comportement du barrage;

c) les appareils de mesure de ces grandeurs;

d) le nombre et la répartition de ces appareils;

e) la fréquence des observations.

Le rapport Français indique, suivant les types de barrage, les paramètres significatifs de leur comportement et les dispositifs de mesure correspondants. Il souligne qu'il n'est pas toujours possible de faire un choix optimal de ces paramètres; l'optimisation du dispositif (abandon de certaines mesures, quelquefois,

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(1) Bulletin 41 : *L'automatisation dans le contrôle de la sécurité des barrages*, 1982.

for sporadic overall verification of the absolute displacements of the dam, its foundations, and the banks of the whole reservoir.

The point as to what is meant by " geodetic methods " is not always made sufficiently clear. If by " geodetic methods " one means all those methods that assume as reference the gravitational field (the local vertical direction), then many are still valid, such as plumb-lines, inclinometers, and geometric levelling, which are still used with success. If, on the contrary, we mean only trigonometric levelling, triangulation and intersection, then it is indeed generally obsolete.

The United States report touches on the possibility of employing satellites for geodetic monitoring. However, this technique, which has already been applied to a number of dams in the United States, calls for a substantial level of technological development, which perhaps is not available in all countries.

While stating the view that it is not possible to speak of a monitoring system in general terms, the South African report emphasizes the need to re-examine and review all dams on a uniform basis, based on suggestions set out in the ICOLD Bulletin No. 41 (1) and proceed with their possible new instrumentation.

The Austrian report expresses the conviction that an adequate monitoring system should keep the " whole " dam under check without, however, incurring prohibitive costs, for example by fitting one block of an ungrouted gravity dam with an extensive monitoring system and providing a limited number of instruments elsewhere to extend the measurements from this block to the rest of the dam. An example is provided to illustrate this principle in greater detail.

The United States report presents a very detailed description of all the steps to be taken for the correct design of a monitoring system.

The Norwegian and Australian reports provide a brief description of not only the instruments employed but also of their installation and the reading procedure.

The Italian and Japanese reports point out that the monitoring system is an integrated whole that involves the following points :

a) the elements that characterize the safety of the dam and its foundation;

b) the quantities that determine or best describe the behaviour of the dam;

c) the instruments for obtaining these quantities;

d) the number and distribution of the instruments;

e) the frequency of the observations.

The French report points out the significant performance parameters according to dam type and the corresponding instrumentation. The report underlines that not always is it possible to make an optimal choice of these parameters; system optimisation (abandonment of certain measurements, sometimes installation of

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(1) Bulletin 41 : *Automated Observation For The Safety Control of Dams*, 1982.

installation d'appareils complémentaires) se fait au fur et à mesure de l'augmentation des connaissances sur le comportement réel de l'ouvrage. Le rapport Français indique également qu'une règle s'est dégagée de l'expérience : il est plus sûr de surveiller soigneusement, fréquemment et rapidement un certain nombre d'appareils placés judicieusement dans l'ouvrage plutôt que de rechercher l'information dans une masse énorme de résultats.

Dans les rapports Portugais et Canadien, on décrit en détail les dispositifs d'auscultation en fonction du type de barrage; pour chaque type, on donne la liste des appareils les plus couramment utilisés.

4. AUSCULTATION SISMIQUE

Pour des raisons évidentes, les pays qui sont les plus étroitement concernés par ce sujet sont l'Australie, l'Italie, le Japon, le Portugal, le Canada et les États-Unis. Il résulte de ces six rapports que le dispositif d'auscultation sismique devrait être choisi en prenant en compte non seulement le type et les dimensions du barrage (facteurs qui déterminent les fréquences naturelles), mais aussi le type et le niveau de sismicité de la zone. Un tel dispositif devrait contrôler l'activité sismique naturelle (tremblements de terre) aussi bien que celle qui est induite par la retenue elle-même ou celle qui provient des conditions locales spéciales (activité minière, explosions, etc.).

En Australie, on fait appel à l'auscultation sismique pour les plus grands barrages seulement, en utilisant le réseau régional sismique ou en le complétant à l'aide d'un capteur « strong motion » installé dans le barrage et sa fondation.

Le rapport des États-Unis rappelle que les résultats obtenus par un dispositif d'auscultation sismique visent à vérifier si le comportement dynamique réel de l'ouvrage, à la suite d'un événement particulier, correspond bien au comportement théorique prévu pour cet ouvrage et se trouve dans les limites déterminées lors du projet.

Le rapport Italien discute des choix fondamentaux pour la réalisation d'un dispositif sismique fiable :

a) choix des appareils les plus convenables en fonction des caractéristiques sismiques du site et du type de barrage;

b) choix des emplacements les plus significatifs;

c) choix du type de dispositif (distribué ou concentré) en fonction de l'endroit où les résultats sont enregistrés.

Dans le rapport Japonais, dans lequel on rappelle la forte sismicité du pays et la haute densité de population, les problèmes fondamentaux de l'auscultation sismique et les solutions possibles sont illustrés, avec un luxe de détail, par de nombreux exemples concernant aussi bien les barrages en béton que ceux en remblai. De plus, le rapport insiste sur le fait que bien que le Japon soit sousmis à un grand nombre de forts tremblements de terre, aucun des grands barrages construits après la guerre n'a subi de dégâts sérieux, à l'exception d'un barrage de stériles miniers.

complementary instrumentation) can be achieved stepwise to keep pace with increasing knowledge about the actual behaviour of the structure. The French report indicates also that from experience a rule was evolved : it appears safer to follow carefully, frequently and promptly a reduced number of instruments, judiciously placed in the structure, rather than look for information in a huge amount of data.

In the Canadian and Portuguese reports the monitoring systems are extensively described with reference to different types of dams; the most commonly used instruments are listed for every type.

4. SEISMIC MONITORING

For obvious reasons, the countries most closely involved with this subject are Australia, Italy, Japan, Portugal, Canada and United States. All six reports take the view that the seismic monitoring system should be selected taking into account not only the type and size of the dam (factors that determine the natural frequencies) but also the type and level of earthquakes in the area. Such a system has to monitor the natural seismic activity (earthquakes), as well as that induced by the reservoir itself or by special local conditions — mining, explosions, etc.

In Australia seismic monitoring is applied only to the largest dams and this is carried out by using, or partly integrating, the regional seismographic network and a strong-motion sensor system installed ad hoc in the dam and its foundations.

The United States report highlights the fact that the main purpose of data acquired through a seismic monitoring system is to verify whether the real dynamic behaviour of the structure following a particular event agrees with that theoretically predicted for the structure and is within the design limits.

The Italian report weighs the basic choices for the realization of a reliable seismic system :

a) choice of the most suitable instruments according to the seismic characteristics of the site and type of dam;

b) choice of the most significant positions;

c) choice of the type of system : distributed or concentrated, according to where the data are recorded.

In the Japanese report, in which stress is laid on the strong seismic nature of the country, as well as on the high population density, the basic problems of seismic monitoring and the possible solutions are illustrated with considerable detail by means of several actual case histories dealing with both concrete and fill dams. Moreover, the report emphasizes the fact that although Japan has been subjected to a large number of strong earthquakes, none of the large post-war dams have suffered serious damage, with the exception of a tailings dam.

Dans le rapport Canadien, on souligne la nécessité de mesurer l'activité sismique naturelle avant la construction du barrage; de cette façon, la sismicité induite peut être mise en évidence.

Au Portugal enfin, le dispositif d'auscultation dynamique est en général du type transportable. Il est utilisé pour mesurer les vitesses et les accélérations dans les ouvrages au voisinage desquels des événements particuliers peuvent se produire (explosions, ouverture des pertuis de fond, etc.). Il n'y a d'installation permanente que sur un barrage seulement pour l'auscultation des phénomènes sismiques.

5. FRÉQUENCE DES MESURES

Pratiquement tous les rapports sont d'accord sur l'opportunité de lier la fréquence des mesures aux différentes périodes de la vie de l'ouvrage, à savoir, construction, premier remplissage de la retenue et exploitation normale, en tenant compte chaque fois du type de mesure. Cependant, la fréquence peut être modifiée lorsque le vieillissement apparaît ou quand des événements exceptionnels surviennent : périodes où le réservoir est à son plus haut niveau du fait des crues, forts tremblements de terre, périodes où le barrage et sa fondation ont un comportement qui semble anormal. Les valeurs numériques de ces fréquences considérées comme acceptables pour chacune de ces périodes, et qui ne varient pas beaucoup d'un pays à l'autre, sont présentées sous forme de tableaux dans quelques rapports (Japon, États-Unis et Canada) ou simplement énumérées dans d'autres (Italie, Portugal, Suisse). Le rapport Autrichien fait seulement référence aux tableaux qui figurent dans le Bulletin n° 41 de la CIGB.

Pour les auteurs Italiens et Canadiens, le dispositif de mesures devrait être partiellement ou entièrement automatisé, les mesures pouvant être alors effectuées avec une bien plus grande fréquence que lorsqu'elles sont faites manuellement. Dans de tels cas, il est possible d'obtenir des résultats en enregistrement presque continu ou du moins à un intervalle par exemple de 10 minutes, ce qui est certainement très court, compte tenu de l'évolution du phénomène qui concerne le comportement statique de l'ouvrage. Cependant, dans ce cas, et sauf conditions particulières, les résultats obtenus ne sont pas tous stockés; la fréquence d'enregistrement la plus convenable est choisie dans chaque cas.

6. AUTOMATISATION DU DISPOSITIF D'AUSCULTATION

Les expériences et les avis diffèrent beaucoup d'un pays à l'autre. Ainsi, certains pays (Autriche, Italie, Japon, Norvège, Canada, Portugal et États-Unis), pour lesquels l'automatisation est maintenant obligatoire, ont installé des dispositifs de lecture automatique sur un certain nombre d'ouvrages. D'autres pays (France, Afrique du Sud et Suisse) entrevoient dans cette solution davantage le danger de la perte de la vigilance humaine que les bénéfices incertains qui peuvent en résulter.

Cependant, les pays les plus favorables à une solution automatique, non seulement réservent à l'homme le jugement final et l'appréciation décisive de la sécurité de l'ouvrage, mais reconnaissent aussi la nécessité de l'observation visuelle à des cadences opportunes et par des méthodes appropriées.

In the Canadian report the need to measure the natural seismic activity before dam construction is underlined; in this way the induced seismic activity can be evidenced.

In Portugal, lastly, the dynamic monitoring system is generally of the movable type. It is used in order to measure velocities and accelerations on structures in whose proximity relevant events are occurring (blasts, outlet operations, etc.). On one dam only there is a permanent installation, whose aim is to monitor seismic events.

5. FREQUENCY OF MEASUREMENTS

Almost all the reports agree on the advisability of relating frequency of measurement with different stages of the life of the structure, namely construction, first reservoir filling, and normal operation, taking into consideration the type of measurement. However, frequency should be modified during periods when exceptional events occur, such as during high reservoir stages (floods) and following strong earthquake shaking, and also during periods when dam and foundation behaviour is deemed abnormal, and events related to ageing of the structure. Numerical values of these frequencies considered suitable for each of these periods, which do not greatly vary from country to country, are in some cases presented in tables (Japan, United States and Canada) and in other cases simply listed in the text (Italy, Portugal, Switzerland). The Austrian report simply makes reference to pertinent tables in Bulletin No. 41 for the frequencies of readings.

The Italian and Canadian reports point out the fact that should the measurement system be partly or entirely automatic, the measurements can be executed with a much higher frequency than when made manually. In such cases, it is possible to obtain data in an almost continuous manner, or at any rate, or at an interval, for example, of 10 minutes, that is certainly very short in relation to the evolution of the phenomena that involve the static behaviour of the structure. However, in this case, except for particular conditions, the data so obtained are not all stored; the most suitable recording frequency is selected for each occasion.

6. MONITORING SYSTEM AUTOMATION

The experience and views of the various countries on this subject show substantial differences. Thus, countries including Austria, Italy, Japan, Norway, Canada, Portugal and United States, for whom automation is by now obligatory, have in greater or less measure already installed automatic reading and acquisition systems on a number of structures. Other countries, namely France, South Africa and Switzerland, perceive in this solution rather more the danger of the loss of visual (human presence) inspection in relation to the evaluation of safety (or otherwise) than the dubious benefits that might be gained from it.

In this context, it is to be noted, however, that even those countries that are inclined towards an automatic solution not only entrust to humans the final and decisive evaluation of the safety of the structure, but also acknowledge the necessity of visual inspection, on a suitable time and procedure basis.

Dans le rapport Suisse, la présence d'un gardien au barrage est jugée essentielle et c'est lui qui doit être le premier à identifier et à signaler l'apparition des phénomènes anormaux.

Le rapport Français indique que l'enregistrement en continu de certaines lectures et le traitement automatique des résultats sont concevables pendant la période du premier remplissage en vue d'obtenir une très grande masse de données pendant une courte période. En exploitation normale, le traitement des données est aussi automatisé dans une large mesure. D'un autre côté, la télétransmission des lectures de certains appareils, comme le pendule, a été développée notamment pour les barrages en haute montagne qui sont inaccessibles en hiver. Par contre, l'automatisation complète du contrôle, c'est-à-dire la télétransmission du niveau de sécurité du barrage et, le cas échéant, de l'alerte n'a pas été retenue, la tâche délicate d'interpréter le comportement du barrage restant du ressort de l'ingénieur.

Pour l'Afrique du Sud aussi, l'automatisation est une solution à laquelle on ne doit recourir que si, pour une raison quelconque, il n'est pas possible d'avoir une surveillance humaine.

Dans ce dernier rapport, on mentionne toutefois la nécessité du contrôle du barrage en temps réel réalisé en équipant les équipes de techniciens de calculateurs de poche avec lesquels ils peuvent calculer les résultats prévus et les comparer avec les mesures. Cette manière de faire peut être considérée comme un type d'auscultation semi-automatique.

Pour l'Italie, au contraire, la collecte automatique des données permet :

— d'avoir des mesures plus fiables, plus homogènes et obtenues avec la fréquence désirée;

— d'effectuer un premier contrôle des résultats et toute une série d'autotests pour la vérification du fonctionnement correct des capteurs et de tout le dispositif;

— de permettre la réalisation d'un contrôle continu en ligne et en temps réel;

— de mettre toutes les données sur un support adapté au traitement automatique ultérieur;

— de concentrer l'attention du technicien sur les cas où un comportement anormal de l'ouvrage est évident et d'avoir en main un vaste et fiable ensemble de données.

Le rapport Japonais traite de ce sujet en présentant un tableau détaillé dans lequel on compare les « pour » et les « contre » de l'automatisation. Pour les dispositifs automatiques d'auscultation, on souligne la nécessité d'avoir une maintenance spécialisée effectuée par un personnel technique qualifié.

Le rapport Autrichien traite de la difficulté toujours plus grande d'avoir un personnel digne de confiance en résidence sur le site; cette considération et le fait que les barrages ne sont pas toujours accessibles conduisent à choisir l'automatisation. Dans ce rapport, de même que dans les autres qui sont en faveur de l'automatisation, il est clairement indiqué que ce qu'on appelle l'alarme automatique est et doit rester une alerte technique destinée à attirer l'attention des responsables et n'être en aucun cas une alerte destinée directement aux populations.

Le rapport des États-Unis comporte une annexe entière qui énumère quelques-uns des barrages importants dans lesquels des dispositifs automatiques ont été installés, ainsi que les barrages qui, dans un proche avenir, seront équipés d'un dispositif de ce type. De plus, on indique toutes les grandeurs et les capteurs

In the Swiss report, the presence of the keeper at the dam site is considered essential, and it is he who is the very first to identify and communicate the occurrence of an unusual event.

The French report points out that the « continuous » recording of certain instrument readings and the automatic treatment of data are conceivable during the first filling in order to acquire a large quantity of data over a short period of time. During normal operation, the data treatment is also automated to a large extent. On the other hand, the teletransmission of the readings of certain instruments (e.g. telependulum) has been implemented, above all, for high-mountain dams which are inaccessible in winter time. On the contrary, completely automatic control, i.e. the teletransmission of the degree of safety of the dam (and, if necessary, of the alert) is not contemplated, the delicate function of dam behaviour interpretation pertaining to the engineer.

South Africa also considers complete automation as a solution called for only if for some reason or another human surveillance is not available.

In this latter report, however, mention is made of the need for control of the dam in real time, which can be accomplished by equipping the technical teams with portable computers with which to calculate the forecast data and compare them with those measured. This may be considered as a type of semi-automatic monitoring system.

For Italy, automatic acquisition makes it possible to :

— obtain more reliable, homogeneous data with the frequency desired;

— effect an initial validation of the data and an entire series of auto-tests in order to ascertain the correct operation of the sensors and systems;

— achieve continuous control, on-line and in real time;

— feed all the data acquired into a support suitable for subsequent automatic processing;

— concentrate the attention of the technical personnel towards those cases that signal unusual behaviour of the structure, and have at hand in these instances an ample and reliable body of data.

The Japanese report presents a detailed table in which the pros and cons of automation are compared. For automatic monitoring systems, it stresses the need to assure specialized maintenance that can be carried out only by suitable technical personnel.

The Austrian report deals with the problem of increasing difficulty in the availability of reliable personnel to be resident at the dam site; and this, combined with the fact that dams are not always accessible, necessarily leads to the choice of automation. In this report, as also in the others that favor the automatic solution, it is clearly stated that the so-called " automatic alarm " is and should be a technical alert directed towards alerting those responsible and is in no way an alarm directed towards the population.

The United States report carries an entire appendix that lists some of the important dams in which automatic systems have been installed, as also all those that in the near future are to be equipped with systems of this type. Furthermore, correspondants pour lesquels il est possible d'avoir recours à une acquisition automatique des données.

Le rapport Norvégien considère également que l'utilisation de l'automatisation est acquise mais seulement dans les cas d'ouvrages d'une certaine importance, tandis que la collecte manuelle des données est suffisante pour des ouvrages de plus petite taille.

Le rapport Portugais, tout en admettant que les avantages de l'automatisation sont bien reconnus, souligne néanmoins qu'un plan pour l'automatisation n'est pas d'une urgence particulière du fait qu'au Portugal les barrages sont accessibles toute l'année. Pour les barrages en remblai, il n'y a eu jusqu'ici aucune automatisation.

Dans le rapport Canadien, on rappelle que les dispositifs pourraient produire de fausses alertes; en conséquence, il faudrait installer plusieurs systèmes d'alerte et l'entrée en vigueur du plan d'alerte ne devrait se faire que lorsque plusieurs de ces dispositifs en auraient donné le signal.

Finalement, dans tous les rapports favorables aux dispositifs automatiques d'auscultation, on indique clairement que le rôle essentiel de ceux-ci est de télétransmettre les données au centre de surveillance.

7. ANALYSE DES RÉSULTATS DE MESURES

On admet généralement qu'une maîtrise efficace de la sûreté des barrages nécessite une interprétation des mesures dans un délai très court. Cependant, en ce qui concerne les méthodes d'interprétation ou d'analyse, les pratiques sont différentes et les points de vue variés. Il va sans dire que cela dépend beaucoup de l'utilisation ou non des ordinateurs avec lesquels il est possible de stocker les résultats et d'obtenir différents graphiques en un temps très court.

De toute façon, ce traitement manuel ou automatique est le point de départ pour un premier examen des résultats. Une deuxième étape consiste à comparer les résultats aux prévisions. Tous les pays sont d'accord sur ces deux étapes (Autriche, France, Italie, Japon, Portugal, Afrique du Sud, Suisse et États-Unis), mais l'accent mis sur cette deuxième étape et sur son importance peut varier de même que la façon dont sont obtenues les prévisions.

La méthode la plus simple et la plus répandue est la méthode statistique signalée par la France, le Japon et la Suisse, qui permet de prévoir des valeurs sur le comportement à venir de l'ouvrage, sur la base de calculs de type statistique (régression) appliqués aux résultats de mesures obtenus au cours d'un certain nombre d'années d'exploitation.

La méthode déterministe utilisée plus spécialement par l'Italie est basée, au contraire, sur un véritable modèle mathématique de l'ouvrage, dont il est possible, en fait, de déduire les valeurs prévues d'une grandeur contrôlée indépendamment de l'histoire de celle-ci.

En Autriche, on utilise une approche mixte : une étude statistique permet d'améliorer les paramètres introduits dans le modèle déterministe.

it offers a list of all those quantities, and the related sensors, for which it is possible to have recourse to automatic acquisition.

The Norwegian report also takes the utilization of automatic systems for granted, but only in the case of structures of a certain importance, while manual acquisition suffices for those of a smaller size.

The Portuguese report underlines that, although all the advantages of automation are clearly recognized, the development plan for automation does not foresee any particular urgency, owing to the fact that Portuguese dams are accessible all along the year. As for embankment dams, no automation activity has been yet undertaken.

The Canadian report emphasizes the fact that automatic systems are likely to send false alerts; consequently, more than one alert system should be installed, and emergency action should be initiated only after several of them signal alert conditions.

Finally, all the reports that view automatic monitoring systems favourably make it clear that an essential part of the system is the possibility of telecommunicating the data to a manned station.

7. ANALYSIS OF INSTRUMENTAL DATA

It is generally accepted by all parties that effective control of dam safety requires that the measured data be interpreted in the shortest possible time following the readings. However, in regard to the methods of interpretation and analysis of such data, there are different practices and varying viewpoints. Needless to say, much depends on the use or otherwise of the resources offered by electronic computers, with which it is possible, once the data have been stored, to obtain different types of graphics within a very short time.

Whether effected manually or automatically, this is the point of departure, agreed upon by all, for an initial examination of the measurements. A second stage consists in comparing the measured data and corresponding forecast values. This aspect also is subscribed to by all the countries (Austria, France, Italy, Japan, Portugal, South Africa, Switzerland and United States); but variations are to be found in the emphasis and the importance attributed to this stage, as well as in the procedures employed for obtaining the forecast data.

The simplest and the most widespread method is the statistical one reported by France, Japan and Switzerland, which makes it possible to obtain the forecast data on the basis of statistical type (regression) analysis of the progressive history of the structure.

The deterministic method, employed especially by Italy, is based instead on a true mathematical model of the structure; from such a model it is, in fact, possible to deduce the forecast values of a quantity under check independently of the history of the same.

In Austria a mixed approach is used : a statistical modelling permits improvement of parameters introduced into the deterministic model.

En plus de l'archivage, de l'établissement de graphiques, des calculs préliminaires (moyennes, moyennes mobiles, séries de Fourier, etc.) et d'une comparaison avec les prévisions, une étude correcte des mesures doit cependant inclure normalement une estimation sérieuse de la tendance de l'évolution des écarts, c'est-à-dire de l'évolution, en fonction du temps, des différences entre les valeurs mesurées et celles calculées.

A ce sujet, le rapport Italien décrit l'utilisation de différentes « bandes de tolérance », c'est-à-dire des zones qui déterminent une évolution différente du comportement de l'ouvrage (normal, alerte légère, alerte grave) suivant l'endroit où la valeur de l'écart se situe.

Le rapport Français, outre la méthode d'étude statistique, mentionne également une autre méthode consistant à comparer les paramètres mesurés avec leurs valeurs telles qu'elles résultent du calcul dans l'établissement du projet de barrage. La comparaison du modèle mathématique avec l'ouvrage réel est maintenant possible grâce au progrès réalisé dans les méthodes de calcul des barrages.

Enfin, une dernière considération sur l'étude des mesures est présentée par quelques pays (États-Unis, Italie, Portugal, France, Autriche) : l'appréciation du comportement de l'ouvrage, quand il provient de mesures, ne doit pas être basée sur une seule mesure mais sur les évolutions corrélées de plusieurs d'entre elles.

8. VIEUX BARRAGES OU BARRAGES SANS DISPOSITIF ADÉQUAT D'AUSCULTATION OU PRÉSENTANT DES PROBLÈMES PARTICULIERS

Tous les rapports n'ont pas traité directement de ce sujet.

La France et le Japon se bornent à donner quelques exemples pour illustrer le problème.

Le rapport Français signale toutefois qu'il existe des règlements permettant d'engager une procédure spéciale d'examen pour les vieux barrages; un tel examen peut aussi conduire à la mise en place de dispositifs d'auscultation ou à l'amélioration de ceux existants. D'une manière générale, les dispositifs d'auscultation installés sur ces barrages anciens seront assez simples et ils auront pour objectif de détecter des anomalies préoccupantes pour la sécurité des ouvrages et non de fournir un état complet de leur comportement.

Dans le rapport Canadien, on souligne la nécessité d'exécuter un examen général du barrage tous les cinq ou six ans, en remettant au goût du jour, quand c'est nécessaire, le système de mesures.

Par contre, le rapport Italien traite du problème d'un point de vue général et avance le concept de la réalisation d'un « check-up » ou d'un « examen certifié » pour tous les vieux barrages ou ceux qui présentent des problèmes spéciaux. Un tel check-up devrait être répété environ tous les dix ans et devrait comporter la vérification globale des points suivants :

a) ré-examen du projet et de toutes les archives donnant des informations sur la vie de l'ouvrage;

Besides storing, diagramming, preliminary, analysis — averages, moving averages, Fourier analysis, etc. — and comparison with similar forecast values, a correct analysis of data must, however, also include an in-depth evaluation of the deviation trend, i.e., the trend in time of differences between measured data and calculated values.

In this context, the Italian report describes the use of different « tolerance bands », that is to say, areas that determine a different evolution of the behaviour of the structure (normal, light alert, serious alert), depending on where the deviation value falls.

The French report, beyond the statistical analysis method, indicates another method as well, consisting of the comparison of measured parameter values with the corresponding values as computed in the dam design. The " mathematical model vs. actual structure " comparison is nowadays possible thanks to the advances achieved in computational dam analysis.

Lastly, a final consideration on the analysis of data (United States, Italy, Portugal, France, Austria) is that the evaluation of the behaviour of the structure to be derived from data should not be based on the consideration of a single measurement alone, but by correlating the trends of several quantities obtained.

8. OLDER DAMS OR THOSE DEVOID OF AN ADEQUATE MONITORING SYSTEM; DAMS WITH SPECIAL PROBLEMS

Not all the reports deal with this subject directly.

France and Japan present some actual case histories by way of illustrating the problem.

The French report, moreover, emphasizes the fact that there are existing regulations in the country that make it possible to activate a special revision procedure for older dams; such revision may also lead to the placing of instrumentation or improving the monitoring system. Generally speaking, the monitoring instrumentation installed in these old dams must be very simple and their aim should be to detect anomalies significant for dam safety, not to give the complete situation of dam behaviour.

The Canadian report mentions the necessity of carrying out a general inspection and check-up of the dam every 5-6 yrs., updating where necessary the monitoring system.

The Italian report deals with the problem from a more general standpoint and puts forward the concept of the execution of a check-up or " certified control " for all the older dams or those with special problems. Such a check-up should be repeated about every 10 years and would consist of verifying overall the following points :

a) re-examination of the design and of all the documentation related to the information on the life of the structure;

b) révision de tout le système de mesures pour s'assurer qu'il est complet et adéquat;

c) étude de toutes les données sur l'histoire de l'ouvrage;

d) recherche en vue de la détermination des caractéristiques physico-mécaniques et géométriques du barrage et de sa fondation;

e) estimation des conditions de stabilité; établissement d'un modèle mathématique et/ou physique de l'ouvrage et de ses fondations;

f) création ou mise au point de modèles de prévisions pour un contrôle du comportement statique et dynamique du barrage;

g) révision et mise à jour du système d'auscultation et de l'élaboration des résultats;

h) contrôle de l'état des matériaux au moyen d'essais non destructifs;

i) rédaction d'un code de surveillance pour les responsables de la sécurité de l'ouvrage.

A partir des résultats de tous ces examens et calculs, il est possible d'effectuer une estimation objective de la sécurité de l'ouvrage, de la nécessité ou non de modifications et, si oui, de la mise en œuvre de celles-ci ou, dans les cas extrêmes, de la mise hors service de l'ouvrage en prenant en compte également les facteurs économiques.

En Suisse, on procède à un contrôle de ce genre tous les 5 ans, notamment pour ce qui concerne les paragraphes *b, c, f, g* et *i* ci-dessus.

9. APPAREILS NOUVEAUX

Les nouveautés et les progrès concernant les appareils sont exposés ci-après :

— ÉMISSION ACOUSTIQUE : système basé sur l'émission acoustique pour la surveillance de la formation de fissures dans le béton - AUTRICHE.

— JAUGE DE CONTRAINTE EN FORAGE : instrument à corde vibrante posé en forage pour la mesure des variations de contraintes dans le béton - AFRIQUE DU SUD.

— DISTOFOR : instrument pour la mesure des déplacements relatifs en plusieurs points d'un forage en fondation - FRANCE.

— EDME (Electronic Distance Measuring Equipment) : système pour la mesure de précision des mouvements des barrages - ÉTATS-UNIS.

— EXTENSOFOR : comme le DISTOFOR, mais avec l'emploi d'une sonde mobile - FRANCE.

— LADIR : système laser pour la surveillance du comportement dynamique de grandes structures - ITALIE.

— LASER PLUMB-LINE : système de pendule optique au laser pour la mesure des déplacements de points des barrages, en puits incliné - AUTRICHE.

— MAGNETIC MEASURING DEVICE FOR ASPHALTIC CONCRETE CORE WALL DEFORMATIONS : système de mesure magnétique pour les déformations d'un noyau en béton bitumineux - AUTRICHE.

— CABLES AVEC FIBRE OPTIQUE : JAPON.

— REMOTE CONTROL ROBOT SYSTEM OF SUBMERGED INSPECTION OF DAMS AND AQUEDUCTS : système de contrôle à distance par robot pour l'inspection sous l'eau de barrages et conduites d'eau - JAPON.

b) revision of the entire measuring system installed and verification of its completeness and adequacy;

c) analysis of all the data on the history of the structure;

d) investigation for the determination of the physical, mechanical and geometrical characteristics of the dam and its foundation;

e) evaluation of stability conditions; mathematical and/or physical modelling of the structure and foundations;

f) setting up or adjustment of the prediction models for the control of the static and dynamic behaviour of the dam;

g) revision and updating of the monitoring system and of data processing;

h) checks on the condition of the materials via non-destructive investigations;

i) drafting of the surveillance procedure for those responsible for the safety of the structure.

From the results of all these analyses, it is possible to issue an objective evaluation on the safety of the structure, on the necessity or otherwise of modifications, the articulation of the latter, or in extreme cases the advisability, taking into consideration economic factors, of taking the structure out of service.

In Switzerland a control of this type (especially for the above mentioned paragraphs *b, c, f, g* and i) is carried out every 5 years.

9. NEW INSTRUMENTS

Innovations and advances in the field of instruments are set out hereunder :

— ACOUSTIC EMISSION (system based on acoustic emission for monitoring the formation of cracks in concrete) - AUSTRIA.

— BOREHOLE STRESSMETER (vibrating wire, instrument installed in a borehole for the measurement of stress variations in concrete) - SOUTH AFRICA.

— DISTOFOR (Instrument for the measurement of relative displacements in several points of the foundation) - FRANCE.

— EDME (Electronic Distance Measuring Equipment - System for the precision measurement of the movements of dams) - UNITED STATES.

— EXTENSOFOR (same as the DISTOFOR but with the use of a mobile probe) - FRANCE.

— LADIR (Laser system for observation of the dynamic behaviour of large structures) - ITALY.

— LASER PLUMB-LINE (alternative system to the plumb-line for the measurement of displacement of points of the dam in inclined shafts) - AUSTRIA.

— MAGNETIC MEASURING DEVICE FOR ASPHALTIC CONCRETE CORE WALL DEFORMATIONS - AUSTRIA.

— OPTICAL FIBRE CABLES - JAPAN.

— REMOTE CONTROLLED ROBOT SYSTEM OF SUBMERGED INSPECTION OF DAMS AND AQUEDUCTS - JAPAN.

— MICROMÈTRE A GLISSEMENT : instrument pour mesurer les déformations axiales le long d'un forage - AFRIQUE DU SUD, AUTRICHE ET SUISSE.

— STREAMING POTENTIAL METHOD : méthode pour la mesure des pertes par infiltration - ÉTATS-UNIS.

— TÉLÉPENDULE (optique ou inductif) : transmission à distance des lectures du pendule.

— THERMOGRAPHIE : système pour la détermination des températures superficielles des parements des barrages - ITALIE et, pour la détermination des infiltrations, ÉTATS-UNIS.

— INFRA RED LASER FOR DISTANCE MEASUREMENT : laser à l'infra-rouge pour mesures de distance - JAPON.

10. BARRAGES CITÉS DANS LES RAPPORTS NATIONAUX

Enfin, dans presque tous ces rapports, on donne de nombreux exemples d'auscultation de barrages. Les différents exemples présentés sont rappelés ci-après :

Australie	: Dartmouth	— barrage en terre et enrochement
	Cethana	— barrage en béton et enrochement
	Hume	— barrage-poids
	Prospect	— barrage en terre
Autriche	: Kölnbrein	— barrage-voûte
	Zillergruendl	— barrage-voûte
	New Tauernmoos	— barrage-poids
	Finstertal	— enrochement
	Moell	— barrage-voûte
France	: Grand'Maison	— barrage en terre et enrochement
	Laparan	— barrage-voûte
	Laouzas	— barrage-voûte
	Guerlédan	— barrage-poids
Italie	: Ridracoli	— barrage poids-voûte
Japon	: Kurobe	— barrage-voûte
	Fukada	— barrage en terre
	Kisenyama	— barrage en enrochement
	Gosho	— barrage-poids et enrochement
	Marunuma	— barrage à contreforts
	Tagokura	— barrage-poids
Norvège	: Svartevann	— barrage en terre
Portugal	: on cite des barrages mais sans leurs noms.	
Afrique du Sud	: Elandsjagt	— barrage en terre et enrochement
	Pongolapoort	— barrage-voûte
	Vaal	— barrage-poids

— SLIDING MICROMETER (instrument to measure axial deformation along a borehole) - SOUTH AFRICA, SWITZERLAND, AUSTRIA.

— STREAMING POTENTIAL METHOD (method for the measurement of seepage losses) - UNITED STATES.

— TELEPENDULUM (optical or inductive; long-distance transmission of pendulum readings).

— THERMOGRAPHY (System for the determination of the surface temperature of dam faces) - ITALY and, for determination of seepage, UNITED STATES.

— INFRA RED LASER FOR DISTANCE MEASUREMENT - JAPAN.

10. DAMS CITED IN NATIONAL REPORTS

Finally, almost all the reports include several examples of the monitoring of actual dams. Once more, it is deemed useful to summarize here the various cases illustrated :

Australia :	Dartmouth	— earth and rockfill dam
	Cethana	— concrete and rockfill dam
	Hume	— gravity dam
	Prospect	— earth dam
Austria :	Kölnbrein	— arch dam
	Zillergruendl	— arch dam
	New Tauernmoos	— gravity dam
	Finstertal	— rockfill dam
	Moell	— arch dam
France :	Grand'Maison	— earth and rockfill dam
	Laparan	— arch dam
	Laouzas	— arch dam
	Guerlédan	— gravity dam
Italy :	Ridracoli	— arch gravity dam
Japan :	Kurobe	— arch dam
	Fukada	— earth dam
	Kisenyama	— rockfill dam
	Gosho	— concrete gravity and rockfill dam
	Marunuma	— buttress dam
	Tagokura	— gravity dam
Norway :	Svartevann	— earth dam
Portugal :	dams are cited but without names	
South Africa :	Elandsjagt	— earth and rockfill dam
	Pongolapoort	— arch dam
	Vaal	— gravity dam

Suisse : Santa Maria — barrage-voûte mince
Hongrin — barrage-voûte mince
Zervreila — barrage-voûte
Grande Dixence — barrage poids
Luzzone — barrage-voûte
Valle di Lei — barrage-voûte
Göscheneralp — barrage en remblai
États-Unis : New Bullards Bar — barrage-voûte
Morrow Point — barrage-voûte
Glen Canyon — barrage poids-voûte
Galesville — barrage-poids avec béton compacté au rouleau
Oroville — barrage en terre
Trinity — barrage en terre
Carter — barrage en terre

11. CONCLUSIONS

Comme déjà mentionné dans l'Avant-Propos, on a cherché, dans cette Note de Synthèse, à présenter au lecteur les sujets traités dans les rapports nationaux en mentionnant ceux dans lesquels chacun de ces thèmes est développé le plus largement. On n'a pas voulu porter un jugement sur les solutions proposées ni sur la manière de les exposer : une telle appréciation est laissée au lecteur.

En bref, l'absence de critique concerne à la fois les idées de base exprimées dans les différentes contributions et la forme des exposés (clarté, détail, compréhension, etc.).

Il paraît donc indispensable de ne pas se limiter à la lecture de la Note de Synthèse, mais d'examiner en détail les onze rapports nationaux afin de tirer pleinement profit des réalisations et expériences propres à chaque pays.

Toutefois, il a paru intéressant de mettre en évidence ci-après quelques points qui se retrouvent plus ou moins dans tous les rapports, ainsi que quelques conceptions fondamentales sur l'auscultation qui sont traitées plus en détail dans le Bulletin 60.

1. Chaque barrage constitue un cas particulier qui doit être traité individuellement par une équipe qualifiée.

2. Le niveau de sécurité d'un barrage est assuré essentiellement au stade du projet, de sorte que les dispositifs d'auscultation doivent être conçus à ce stade, en accord avec les critères de projet.

3. L'automatisation des systèmes d'auscultation permet de traiter de grandes quantités de données et d'exécuter les calculs nécessaires. Cependant, l'estimation critique des résultats et la responsabilité d'apprécier le degré de sécurité des barrages doivent être confiées à une équipe technique qualifiée incluant, si possible, le projeteur.

Switzerland : Santa Maria — thin arch dam
Hongrin — thin arch dam
Zervreila — arch dam
Grande Dixence — gravity dam
Luzzone — arch dam
Valle di Lei — arch dam
Göscheneralp — embankment dam
United States : New Bullards Bar — arch dam
Morrow Point — arch dam
Glen Canyon — arch gravity dam
Galesville — gravity dam with rolled concrete

Oroville — earth dam
Trinity — earth dam
Carter — earth dam

11. CONCLUSIONS

As was mentioned in the beginning, in this brief Overview an attempt has been made to provide an indication for the reader as to which subjects have been dealt with in the National reports and the area of major emphasis. It has neither been the intention, nor has it been thought desirable, to express any evaluation whatsoever regarding either the solutions put forward or the manner in which they are presented; such evaluation being left to the reader alone.

In brief, the absence of critique is deliberate in regard to both the basic viewpoints of the various contributions and the formal aspects of the presentations, such as clarity, detail, comprehensiveness, etc.

It is thought indispensable to suggest to the reader that he should not confine his reading to this overview only, but that the most useful and exhaustive reading of this Bulletin consists in attentively perusing the reports of the 11 countries to reveal fully the achievements and experiences of the individual nations in performance monitoring of dams.

However, at the end of this Overview it is deemed proper to mention a few points that are more or less present in all the reports and some basic concepts on monitoring that are more fully dealt with in the new edition of Bulletin 60.

1. Each dam is a particular case that should be dealt with individually by an experienced team.

2. The safety level of a dam is mainly established at the design stage. Thus monitoring systems should be defined at this stage and in accordance with design criteria.

3. Automation of monitoring systems provides better possibilities of handling a huge amount of data and performing the necessary computations, but the critical evaluation of the results and the responsibility for ascertaining the degree of safety of the dam must lie with a qualified and expert engineering team. This team should include, whenever possible, the dam designer.

4. On ne doit jamais abandonner l'observation visuelle.

5. Pour l'analyse des résultats, on recommande en général le recours aux prévisions (par l'intermédiaire de modèles statistiques, déterministes ou hybrides).

6. Les appareils d'auscultation doivent être simples, robustes et d'emploi facile, de façon à pouvoir être utilisés par du personnel local peu qualifié.

7. Les mesures doivent couvrir non seulement le barrage lui-même mais aussi ses fondations et les appuis latéraux.

8. Les variables à mesurer peuvent être classées en :

— variables-causales (variations dans l'environnement);

— variables-résultantes (réponses de l'ouvrage aux variations de l'environnement).

Parmi les premières, une importance particulière est attachée aux variations :

— du niveau de retenue;

— de température.

Parmi les autres, on doit mentionner, en particulier :

— les déplacements;

— les débits de fuite;

— les déformations;

— les sous-pressions;

— les pressions interstitielles.

9. L'importance des mesures, leur fréquence et les types d'instruments les plus convenables dépendent fortement du type du barrage, de la période de la vie de l'ouvrage concernée et de l'importance du barrage lui-même en ce qui concerne ses dimensions, ses buts et la présence éventuelle de populations ou de biens à l'aval du barrage (voir Bulletin n° 41).

10. On doit apporter un soin particulier à l'auscultation sismique, aussi bien pour connaître l'intensité et le déroulement des phénomènes que pour apprécier l'intégrité ou les dégâts éventuels subis par l'ouvrage.

11. La même importance doit être accordée à la prévision des crues.

12. Les appareils ne doivent pas être concentrés dans des zones particulières du barrage, mais au contraire distribués de manière à ausculter l'ensemble de l'ouvrage.

13. Pour les « vieux barrages », c'est-à-dire ceux de 20 à 30 ans d'âge et plus, il est bon d'envisager des check-up tous les 5-10 ans, afin d'estimer plus à fond l'état de l'ouvrage et de sa détérioration éventuelle et de revoir son dispositif d'auscultation.

Le problème des barrages anciens n'a pas été traité dans tous les rapports nationaux avec une ampleur suffisante, bien que son importance et son grand intérêt soient reconnus par tous.

Ce problème des vieux barrages présente en effet deux aspects :

— vérification que ces vieux barrages satisfont aux règlements actuels de sécurité; moyens à mettre en œuvre dans le cas contraire pour que le niveau de sûreté du barrage aille de pair avec les progrès de la technique;

4. Direct visual observations should never be abandoned.

5. For the analysis of the results the use of forecast values (by means of a deterministic model or a statistical one or by hybrid approach) is generally recommended.

6. The instruments used in the monitoring system should be simple in design, strong and easy to operate so as to be used by moderately qualified local staff.

7. The measurements should cover not only the dam but also its foundations and abutments.

8. The monitored quantities should be distinguished as :

- causal quantities (environmental variations);
- effect quantities (response of the structure to environmental variations).

Among the first ones of paramount importance are :

- water level;
- temperatures.

Among the second quantities the main ones are :

- displacements;
- seepage losses;
- deformations;
- uplift pressures;
- pore pressures.

9. The importance of measurements, their frequency and the most suitable instrumentation are strongly dependent on the type of dam, on the period of dam life and on the relevance of the dam as concerns its size, purpose and presence of human lives or economic activities downstream of the dam (see Bulletin 41).

10. Particular care should be devoted to seismic monitoring, both in order to know the evolution and intensity of the event and to evaluate the integrity, or the degree of damage, of the structure.

11. A similar importance should be attributed to flood forecasting.

12. The instrumentation should not be concentrated in a limited portion of the structure, but should be suitably distributed so as to keep the whole dam under observation.

13. For old dams (20-30 yrs. and more after their construction) it is recommended to schedule, every 5-10 years, special investigations (check-ups) aimed at a careful evaluation of the dam state, of its deterioration (if any) and of the need to update the monitoring system.

The problem of old dams has not been sufficiently treated in some of the National reports, in spite of the fact that, by general consensus, it is of paramount importance and interest.

The aforesaid problem presents two basic aspects :

- the analysis of compliance of old dams to present-day regulations; means of dealing with the ensuing problems in case such compliance is not satified;

— réexamen de tout le dispositif d'auscultation pour vérifier s'il est encore suffisamment performant; dans le cas contraire, définition des critères de sa rénovation.

Si le second aspect a été discuté — quoique partiellement — dans quelques rapports, le premier, par contre, n'a presque pas été abordé. Il le sera dans une prochaine étude qui vient d'être confiée au Comité par la 56^{e} Réunion Exécutive de la CIGB tenue à San Francisco, en juin 1988.

— the re-appraisal of the whole monitoring system in order to ascertain whether it is sufficiently in line with present state-of-the-art; if not, criteria for its updating so as to maintain the safety level of the dam on a par with the standards dictated by modern techniques.

While the second point has been discussed — albeit partly — in some of the reports, the first one did not receive adequate treatment. It will be covered by new research that the Committee was intructed to undertake by the 56th Executive Meeting held in San Francisco in June 1988.

ANNEXES - APPENDICES

RAPPORTS NATIONAUX	NATIONAL REPORTS
A) AUSTRALIE	A) AUSTRALIA
B) AUTRICHE	B) AUSTRIA
C) CANADA	C) CANADA
D) FRANCE	D) FRANCE
E) ITALIE	E) ITALY
F) JAPON	F) JAPAN
G) NORVÈGE	G) NORWAY
H) PORTUGAL	H) PORTUGAL
I) AFRIQUE DU SUD	I) SOUTH AFRICA
J) SUISSE	J) SWITZERLAND
K) ÉTATS-UNIS	K) UNITED STATES

Appendix A
Annexe A

REPORT BY THE AUSTRALIAN NATIONAL COMMITTEE

1. INTRODUCTORY

Water conservation in Australia over the last 150 years has resulted in the construction of about 400 large dams with the greater proportion developed by authorities responsible for conservation and distribution of water for irrigation, urban and industrial usage and for power generation. These major authorities form the membership of the Australian National Committee on Large Dams (ANCOLD). Over recent decades as the number of and size of dams has increased with valleys below becoming more populated and older dams evidencing effects of aging or non compliance with what is regarded as current sound technical practice, ANCOLD has acted to encourage adequate oversight of safety and surveillance matters related to dams and in promulgation of knowledge and expertise in the field of dam engineering. This has led to the publication of the following documents related to monitoring and surveillance :

— ANCOLD - Guidelines for Operation, Maintenance and Surveillance of Dams (1976);

— ANCOLD - Guidelines for Dam Instrumentation and Monitoring Systems (May 1983).

These documents present practice on surveillance and monitoring systems for major dams in Australia. This contribution to the bulletin on monitoring of dams and their foundations is a brief summary of the detailed treatment of those documents.

2. OBJECTIVES AND SCOPE OF INSTRUMENTATION/MONITORING SYSTEMS

2.1. Objectives

The primary objectives of instrumentation/monitoring systems are to provide confirmation of design assumptions and predictions of performance during the construction phase and initial filling of the reservoir.

Subsequently in the operation phase of the life of a dam the systems provide an early indication of the development of adverse trends in behaviour. Where older dams do not conform with accepted modern criteria these systems are oriented to monitoring as a guide to the need for introduction of works to remedy severe deficiencies. Remedial works may of necessity be carried out with the dam under full or partial storage conditions which will dictate that patterns of structural and seepage behaviour be established prior to commencement of works with close monitoring during construction to allow corrective action to be taken should unsafe trends in behaviour develop.

2.2. Scope of Instrumentation/Monitoring Systems

The number of instruments and their distribution within a dam and its foundations and complementary monitoring systems, depend on the type of dam and foundations, site topography, regional seismicity, etc., and for a new dam, will be oriented primarily to problems envisaged at the design stage. For large dams the increasing trend to use of numerical analysis techniques in the design phase to give a qualitative appreciation of stress/deformation provides a basis for logical disposition of instrument systems in monitoring conformity of the dam with acceptable patterns of behaviour. Particular circumstances relating to each dam will determine that greater or lesser accent be placed on certain areas of instrumentation.

The complexity and extent of monitoring systems to be deployed on a dam while largely dictated by the objectives outlined will in addition be influenced by the " hazard rating " of the dam based on the potential economic loss and loss of life which may stem from a dam failure or mis-operation of the dam or its facilities. When considered in conjunction with the adequacy of the dam and its appurtenant structures when assessed for conformity with modern standards of design, construction, maintenance and operation of large dams, more comprehensive monitoring and surveillance systems may be dictated. The " hazard rating " may vary with future industrial and rural development below a dam dictating amplification of instrumentation and monitoring systems on older dams. Additionally during the life of a dam, adverse structural or seepage trends may warrant expansion of instrumentation and monitoring systems to provide additional emphasis on particular aspects of behaviour.

The ANCOLD Guidelines texts place emphasis on the importance of routine inspection and review systems, in monitoring the behaviour and future performance of a dam. These systems are fundamental to monitoring and surveillance and are an essential complement to instrumentation system.

The systems which warrant consideration in planning, development and implementation of monitoring requirements for new and existing dams are embraced by the following categories :

- Visual Inspection and Reviews,
- Seepage Measurement and Analysis,
- Groundwater/Seepage Pressure Measurement,
- Surface Displacement and Strain Measurement,
- Internal Displacement and Strain Measurement,
- Stress and Load Measurement Systems,
- Hydrometeorological,
- Seismicity Monitoring.

3. INSTRUMENTATION AND MONITORING SYSTEMS

3.1. General

This section briefly presents the range of instrumentation and monitoring systems treated in detail in the ANCOLD Guidelines for Dam Instrumentation and Monitoring Systems (May 1983). The Guidelines text includes details of different types and forms of instrumentation and experience of dam construction/owner authorities relating to installation, operation and maintenance aspects; the guidelines also cover systems such as seepage monitoring (measurement, chemical and biological analysis) precise survey, etc., with treatment of recording, processing and assessment procedures.

Supplier and cost data (relevant to Australia) is given in the text for general guidance and derived from data provided by dam owners in a survey of instrumentation and monitoring systems in use on major dams in Australia.

3.2. Visual Inspections and Reviews

(i) *Routine Visual Inspections* by site personnel. These inspections are made by sub-professional staff who use a detailed visual check list to assess any significant change in behaviour of the dam with alerting of appropriate engineering personnel should untoward behaviour be evident. Inspections should be more frequent during the early operational phase of a new dam (first filling) or, if the dam evidences untoward behaviour as indicated by other monitoring systems. Visual inspections should be made more frequently during and following unusual events such as earth tremors, major flood conditions, rapid drawdown conditions.

(ii) *Inspection and Reviewal of Behaviour by Engineers*

These rigorous inspections/assessments of behaviour and safety by engineers experienced in dam engineering take cognizance of visual inspections and instrumentation readings and must also address the current state of security of the dam related to expanding knowledge of data on floods, seismicity and change in " hazard rating ".

3.3. Seepage Measurement and Analysis Systems

(i) *Measurement*

Seepage collection and measuring systems are provided to assess the amount of seepage through a dam wall and foundations and may involve collection and measurement of total seepage only or an amplified system utilising the natural topography of abutments (complemented by cutoff walls in fill dams) or a number of measuring weirs located along formed collector drains in gallerys of concrete dams to allow collection and measurement from problem areas warranting detailed monitoring. Where foundations are pervious rendering collection of seepage impractical, monitoring of seepage pressure gradients by groundwater measuring wells can be used.

(ii) *Analysis of Seepage*

Seepage flow should be measured at regular intervals with inspection of seepage for discolouration/turbidity or untoward increase an important component of routine visual inspection systems.

Trends in seepage behaviour can provide an indication of development of adverse conditions such as piping, deterioration of drains or grout curtains. Chemical analysis of seepage waters is useful in interpretation of the sources of seepage with providing data indicative of the seepage source.

3.4. Groundwater/Seepage Pressure Measurement

Pore pressures are measured in fill and foundation materials of dams to ensure that patterns of pore pressure and seepage pressure comply with assumed behaviour. Typically in impervious core and foundation materials pressures are monitored during construction to assess compliance of materials with pore pressure/settlement behaviour and subsequently under storage conditions to confirm the effectiveness of barriers to through seepage. Monitoring of pressures in filter/drainage zones is used to assess their ability to act as effective drains with relief of pressure. Systems for concrete dams will normally involve seepage pressure measurement at the concrete to foundation interface and within the foundation to assess the effectiveness of cutoff and drainage systems.

The equipment used in these measuring systems can vary from simple groundwater observation wells to sophisticated pressure measuring tips providing registers of pressure at discrete locations.

The primary requirement for the equipment is that it be reliable, provide registers of pressure to the required degree of accuracy and it should not modify the regime in which it is installed. Time of response to change in pressure varies with type of piezometer with a rapid response requirement dictating use of more sophisticated equipment.

Reliability of reading is directly related to care exercised in design, installation and maintenance of systems and the skill of personnel employed in these operations.

3.5. Surface Displacement and Strain Measurement

(i) *Displacement Measurement*

The deformation behaviour of a dam and its abutments is responsive to age of the dam, geological conditions, fluctuations in storage level and temperature change. Displacement behaviour at typical locations in a dam are monitored by instrumentation, but for a broad monitoring coverage of deformation behaviour providing a register of absolute movement of the dam and abutments, precise survey methods are utilised. It is emphasised that correlation with storage variation and seasonal temperature change is necessary to enable conclusions to be reached on the acceptable repeatability of deformations or whether adverse trends in behaviour are evident.

Surface displacements of a dam are monitored by a precise survey system generally based on a triangulation and/or trilateration network (basic control) which is established with a high degree of accuracy. A subsidiary survey control system for measurement of the deformation is fixed from the basic control system as precisely as the equipment and topography will allow.

Different methods and accuracies are required for fill and concrete dams. The basic and subsidiary control networks, and specialised equipment used for the two types of dams are similar, although the targets vary according to the material in which they are placed.

The number and position of survey targets, and the permissible accuracy/tolerances, are matters for determination by the designers, with methods and equipment used, determined by survey personnel.

Instrumentation used in measurement of displacement involved direct or remove reading inclinometers and tiltmeters at fixed surface locations. Inclinometer probes can be used in surface guide casings affixed the external face (viz. concrete faced dams) to provide continuous measurement of slope variation with integration procedures used to derive displacements along the casing.

(ii) *Strain Measurement*

Measurements of surface strains in fill materials, are made by survey of surface settlement points typically along the crest of a fill dam. Where a more detailed appreciation of strain behaviour in fill materials is required a horizontal crossarm system embedded in a trench with electrical strain meters and fixed rods connecting crossarms is used. Short gauge length electrical strain meters are utilised in applications on concrete faces and concrete dams to monitor joint openings or crack systems.

3.6. Internal Displacement and Strain Measurement

A wide variety of instruments are used in fill dams to provide a register of displacements. These instruments may involve vertical or horizontal crossarms or gauge points embedded in the fill and located at intervals along flexible telescoping pipe systems. The location of the gauge points can be monitored by mechanical, electrical inductance, radio or magnetic probe systems to provide measurement of displacement and strain along the installation. Other pipe systems (grooved or smooth) utilise inclinometer probes to provide slope variation along the pipe from which displacements can be calculated. Hydrostatic settlement gauges (U tube with an overflow weir as the measuring point) are a simple device for measurement of vertical settlement at locations generally in free draining materials.

Internal strain measurements may also involve installations having fixed gauge lengths between embedded points with use of electrical strain meters coupled to connecting rod systems.

Pendulums in vertical holes or shafts in concrete dams are frequently used for measurement of deflections. These may be of the hanging type (line fixed at upper end) or the inverted type (line supported by buoyancy system at upper end). The plumb line is commanded at a number of locations for measurement of displacement relative to fixed reference points.

Strain/joint opening measurement in concrete dams utilise electrical or resistance type strain meters with interpretation of behaviour necessitating measurement of temperature by permanent gauges or probes.

3.7. Stress and Load Measurement

In embankment dams, stress measurements may be required to assess loading on structures or risk of hydraulic fracturing within the core of a dam (this latter case would dictate measurement of pore pressures to complement stress measurements). Such installations will normally involve a group of cells allowing interpretation of principal stresses. Compatability of the cells with adjacent materials is important dictating minimum cell thickness to diameter ratio and cell deflection equivalent to that of the surround materials. Particular care is required in placement of backfill materials and in load calibration of cells.

Stress measurement in concrete has been used on a major dam in Australia; the system utilised Carlson Stress Meters. Readings are used as a guide to acceptable structural performance based on repeatability of stress variation with time and water loading on the dam rather than as an absolute register of stress behaviour.

Load measurement systems are used on concrete dams which have been stabilised by restressable post tensioning cables. The system uses a limited travel hydraulic jack which is used to lift the cable head to provide a measurement of total cable load.

3.8. Hydrometeorological

The ANCOLD Guidelines for Operation Maintenance and Surveillance of Dams (February 1976) outlines the organisation which should be established to operate and maintain major dams in accordance with sound practice. The various recommendations given in that reference also cover, among other matters, public warning procedures which should be detailed for warning in the event of flood or other conditions threatening the safety of the dam and its surroundings.

During construction of a dam and in the operational phase where the dam utilises a gated spillway (with potential to release a major flood downstream in the event of malfunction or failure) or the dam is considered to pose a risk to downstream property and valley residents, a system is instituted for warning of meteorological conditions favouring significant flood inflows into the dam storage. This warning of impending flood conditions is complemented at the onset of flood inflows by telemetering or other measures in supplying data from selected upstream river gauging stations and/or rain gauges.

Where potential exists for impairment of the safety of the dam with sudden release of stored waters, civil evacuation services are advised of flood wave inundation levels and wave travel times down the valley related to evacuation of areas which are threatened.

3.9. Seismicity Monitoring

(i) *General*

In Australia, dam builders are favoured by a relatively stable continent however, for major dams, where storage induced seismicity may occur and for dams located in zones of seismic activity conventional instrumentation systems are amplified to include monitoring of seismic behaviour. This monitoring for major dams involves a *Seismograph Net* probably integrated into a regional net or utilizing in part and supplementing a regional net and *Strong Motion Instrumentation* installed in the dam wall and foundations to provide data on dynamic behaviour.

(ii) *Seismograph Nets*

The Bureau of Mineral Resources in Canberra Australia has a general brief within Australia to provide in co-operation with local state organisations, a national net of seismometers capable of providing a coverage of seismic events in excess of Magnitude 3. Where monitoring of behaviour below this energy level is required local authorities within the various states act for or in co-operation with a dam authority. Monitoring of seismic events in conjunction with storage impoundment or the effect on structures should desirably be integrated into a regional net to provide a probabilistic appreciation of future seismic loading.

Sensitive seismographs should be placed in the vicinity of the dam and storage before construction commences with the aim of gaining an appreciation of frequency and location of earthquakes.

(iii) *Strong Motion Accelerographs*

Strong motion accelerographs are recorders designed to measure acceleration and response of the dam, ancillary structures and foundations. These devices are designed to record the strongest possible ground motions and are normally set to trigger at acceleration thresholds which will provide data related to dynamic behaviour; a commonly adopted threshold in Australian conditions is 0.01 g with ranges extending up to 2 g, dependant on possible response of the structure monitored and seismic activity. With this type of instrument structural response data for minor seismic disturbances and initial motions for larger earthquakes are lost due to the coarseness of the threshold setting.

Until recently the two forms of instrumentation previously described were used to monitor seismic vibrations associated with dams.

Use of the system could however give a gap in ground motion between full scale on the seismograph and the resolution of the accelerograph.

Developments in triggered digital recording have closed the gap between the two areas, and extended the range of tasks that may be undertaken. These recorders may use seismometers or accelerometers, and have a very wide dynamic range of up to 120 dB (1:1 000 000) compared with about 60 dB (1:1 000) which is typical for an analogue recorder. They maintain a continuous record of data in a microprocessor memory, so the first motion from the earthquake is not lost. Multiple channels are sampled synchronously, so three dimensional motion may be studied.

Seismographs with timing accurate to within 0.01 second for periods of up to a month are possible, allowing very accurate location of earthquakes within a network. With a suitable network of four or more seismographs, it is possible to locate microearthquakes to an accuracy of one or two kilometres or better. This is often adequate to delineate active faults, and will give seismicity data over a wide range of magnitudes, allowing more reliable extrapolation for the estimation of long return period large earthquakes.

The design of a system for a particular location requires careful consideration of engineering, geological and seismological factors. The optimum solution will vary considerably from application to application.

4. PROCESSING DATA FROM MONITORING SYSTEMS

(i) *General*

Monitoring and instrumentation systems are oriented primarily to appraisal of structural and seepage behaviour of the dam and foundations. Complementary information, allowing interpretation of behaviour from these systems, involves storage and tailwater level behaviour, air/water temperature and humidity variations and rainfall patterns.

Assessment of data in consideration of acceptable repeatability or whether adverse trends in behaviour are indicated must take cognizance of such ambient conditions where appropriate.

(ii) *During Construction*

During construction of most dams of significant size, site staff normally collect data from instrumentation and as a rule process it on site, from where it is forwarded to the designers for examination. The designers check whether the structure is performing to predictions made at the design stage and recommend changes in construction procedures if required. Data from instruments is recorded in continuous graphical form to allow easy recognition of trends and comparison with design preduction of behaviour.

(iii) *During Filling and Early Life*

During initial filling and until structural and seepage behaviour conforms with safe and predictable trends it is important that data from instrumentation and inspection of the dam be carefully and rapidly processed to allow any corrective action to be taken. Data from monitoring is processed by comparing information as it becomes available with previous data and trends. Results should indicate a progressive decrease in non-recoverable deformation as the structure and foundations stabilise leading to repeatibility of behaviour under cycles of loading, temperature, etc.

Over several years the frequency of monitoring can be decreased. Experienced surveillance personnel should however be available at short notice to inspect and evaluate any report of any unusual behaviour of the structure between routine evaluations.

(iv) *Old Dams*

Old dams may have limited instrumentation in a poorly maintained state. Surveillance organisations which accept responsibility for old dams should, after implementing inspection routines, and if necessary installing new instrumentation, establish procedures for monitoring and processing of data as for routine monitoring of modern dams.

5. FREQUENCY OF OBSERVATIONS

The frequency of instrumentation readings varies during the life of a dam from very frequently during construction and first filling to less frequently when the structure has reached a stable condition and repeatable patterns of behaviour are established. Increased frequency of observation is warranted following unusual events such as earthquakes, or rapid drawdown or flood conditions in excess of previous events. During construction, first filling and until acceptable behaviour is established the frequency of instrumentation readings and monitoring are as required to adequately define behaviour under developing load/seepage patterns with frequent readings continuing through at least one or two cycles of storage level variation and seasonal temperature (particularly on concrete dams where deflections are significantly affected by temperature variation).

Detailed visual inspections complemented by measurement of seepage dependant on availability of site personnel are maintained at a weekly frequency for high hazard dams.

Routine inspection and review of behaviour by engineers is continuous during the early life of a major dam with relaxation to yearly and later three yearly frequency as repeatability of stable and acceptable patterns of behaviour are established.

6. EXAMPLES OF INSTRUMENTATION SYSTEMS ON DAMS

(i) *Dartmouth Dam*

Dartmouth dam (Fig. 1) is an earth and rockfill dam 180 m high located on the Mitta Mitta River in Victoria. The dam has a central impervious core of residual granitic material. The filters are well-graded processed granitic gneiss. The rockfill zones are quary-run granitic gneiss compacted in layers varying from 500 mm adjacent to the filters to 2 m at the faces.

Dartmouth is the highest dam and one of the largest earth and rockfill dams in Australia.

The dam was instrumented to provide during construction, filling and operation, detailed information on pore pressures in the impervious zone, downstream fine filter and foundation. Additional instrumentation was provided to measure total earth and rock pressures in the highly-stressed regions of the embankment and settlement and movement throughout the structure. To achieve this grids of piezometers, pressure cells, settlement devices and movement indicators were installed at the maximum section (Fig. 2).

The majority of piezometers in the dam are hydraulic piezometers of the Imperial College type with high-air-entry-value ceramics and twin tube lead-lines. Two classes of diaphragm piezometers were also installed in the dam viz, hydraulic lifted diaphragm — Glotzl and vibrating wire — Maihak, plus some Strainstall. The diaphragm piezometers were installed to indicate total pore water and pore air pressure during construction.

The basic settlement device in the dam is a hydrostatic settlement cell. These are augmented by two electric settlement installations of the " Idel " type and the surface settlement points. A series of points on the abutments and in the basin area were levelled by geodetic survey from a point about 15 km downstream in order to detect any regional settlement associated with the filling of the dam. Horizontal movement devices are of the tensioned-wire system. This system cannot be used upstream after inundation, and in order to provide some information on upstream movements after that time an inclinometer tube was placed in the fill parallel to the upstream core-filter interface.

Three extensometer installations were provided at the crest of the dam to monitor strains near the abutment due to settlement of the central section of the dam.

The instrumentation functioned well and provided useful results both for the control of construction and for designers of future dams.

(ii) *Cethana Dam*

Cethana Dam is a 110 m high concrete faced rockfill dam and has a crest length of 213 m. The total volume of rockfill is 1.4×10^6 m^3 and the volume of concrete in the membrane is 11 300 m^3. The dam is owned by the Hydro-Electric Commission of Tasmania. Construction of the dam was completed in 1971.

The basic objective in the design of the dam was to minimize deformation of the embankment and the concrete membrane. Fundamental to the design were the requirements that virtually the whole of the embankment be completed before commencing construction of the concrete face. The embankment was constructed of sound well graded rockfill placed and compacted in 0.9 m layers in the main body of the dam with 15 per cent water applied during compaction. All vertical joints in the membrane be plain butt waterstopped joints without any kind of joint filler.

The monitoring system was designed to provide measurement of vertical settlement within the embankment at four locations and deflection in three co-ordinate directions at 15 locations on the membrane at crest level, and at 18 locations on the downstream face. Deflection of the membrane in the vertical and slope directions was measured in three vertical sections and at three other isolated locations.

Normal deflection of the concrete membrane was measured at the same three vertical sections. Movement of the perimetric joint between the membrane and the plinth was measured in the plane of the membrane, at three locations on each abutment and at two locations in the river bed. Strain and temperature in the membrane was measured at 32 locations. No-stress strain and temperature in concrete blocks resting on the membrane at five locations were recorded. Leakage measurement was provided for by a weir at the downstream toe of the dam.

The general arrangement of the system is shown in Fig. 3. The instrumentation involves :

Settlement cells. Hydrostatic settlement cells are equipped with an air tube to maintain atmospheric pressure in the cell; water levelling tubes and an extra tube permit excess water introduced through the levelling tubes to be drained away. The cells contain two weirs set at a fixed vertical distance apart to give two measurements of settlement per cell, thus increasing confidence in the results.

Crest targets. Targets used for observing crest settlement and deflection consist of Wild centering bolts set in the membrane mid-way between vertical joints.

Downstream face targets. One metre lengths of drill steel were set in holes drilled normal to the face.

Anchored wires for membrane deflection. A system of wires, designed to measure vertical and slope deflection at 23 points on the membrane, was abandoned after several years. Slope deflections were found to be largely in error because of the effects of temperature on the stainless steel wires, which represented a large proportion of the quantity to be measured.

Inclinometer installation. Three 76 mm-diameter steel pipes were attached to the membrane. Normal deflections of the membrane are obtained by inclinometer traverses within the pipes.

Perimetric joint meters. The measurement of movement of the perimetric joint between the membrane and the plinth is made with 360 mm-long Carlson type joint meters.

Strain meters. Strain in the membrane is measured by 2 m gauge-length strain meters embedded in the membrane and arranged in 45° and 90° rosettes.

In the 1960s dam designers held doubts as to the likely leakage performance of high decked rockfill dams. Cethana, one of the first decked dams over 100 m high constructed of rolled rockfill, demonstrated satisfactory structural behaviour and a leakage performance at least comparable to that of other types of dams. Since building Cethana, the Hydro-Electric Commission has built a number of similar dams.

The designs and specifications for these were based on the Cethana experience. These dams benefited significantly from the understanding achieved at Cethana through its instrumentation and monitoring.

(iii) *Hume dam*

Hume Dam is located on the Murray River on the New South Wales/Victoria border. The dam comprises a 50 m high concrete gravity section flanked by earth fill embankments. The dam was completed in 1936 and the storage was subsequently increased by the addition of spillway gates. Remedial works to improve stability of the concrete dam under revised design flood and earthquake loading were commenced in 1984. These works involved drilling of deep drainage holes into the foundations and installations of post tensioning cables to anchor the dam to the foundations. Fig. 4 shows a cross section of the dam and instrumentation. Monitoring systems include surveys of wall movements, inclinometers at gallery level and crest level, down the hole twin tube hydraulic piezometers installed in holes drilled into the foundations and hanging pendulums in vertical drill holes in the dam wall.

Because of the importance of the post tensioning system to future stability and low *p*H seepage waters due to iron pyrites minerals in the foundation rock the system adopted involved continuous polyethylene sheathing of the cables for corrosion protection with provision for load monitoring of individual cables at the cable head. The cables are grouted into drilled holes with an anchorage section of about 8-10 m length at the lower end. Above this, the 55 individual strands comprising the cable are encapsulated in grease filled polyethylene tubes allowing future restressing and load monitoring. Monitoring of load is by attachment of a limited travel hydraulic load cell to the cable head. The cell has a capacity to lift the cable head and check the cable load as a guide to creep, relaxation or other losses.

(iv) *Prospect Dam*

Prospect Dam retains a reservoir forming part of the water supply system of Sydney in New South Wales. The dam is owned by the Metropolitan Water Sewerage and Drainage Board and was constructed in the 1890's. In the 1970's remedial works were carried out on the 35 m high earth embankment (see Fig. 5) involving placement of stabilising fill on the downstream face. These works included a filter/drainage system to provide protection against piping of the embankment and foundation clays which were identified as dispersive and as a consequence potentially erodible under the action of seepage from the reservoir. Due to the danger of the stabilising fill inducing high pore pressures in saturated embankment and foundation materials with potential for a slip failure, the fill buttressing was construced in two stages with delay between stages to allow dissipation of pore pressures. Sand drains were introduced into the foundations to improve dissipation. During this operation pore-pressure development and dissipation was monitored by electrical and pneumatic piezometers complemented by standpipe piezometers. Structural behaviour was monitored by survey, settlement gauges and inclinometers. Throughout construction seepage waters were closely monitored for any sign of increase in volume. The chemistry of seepage waters was also monitored by conductivity meters as a guide to potential for piping of the dispersive clay materials by fresh (low conductivity) seepage water from the reservoir.

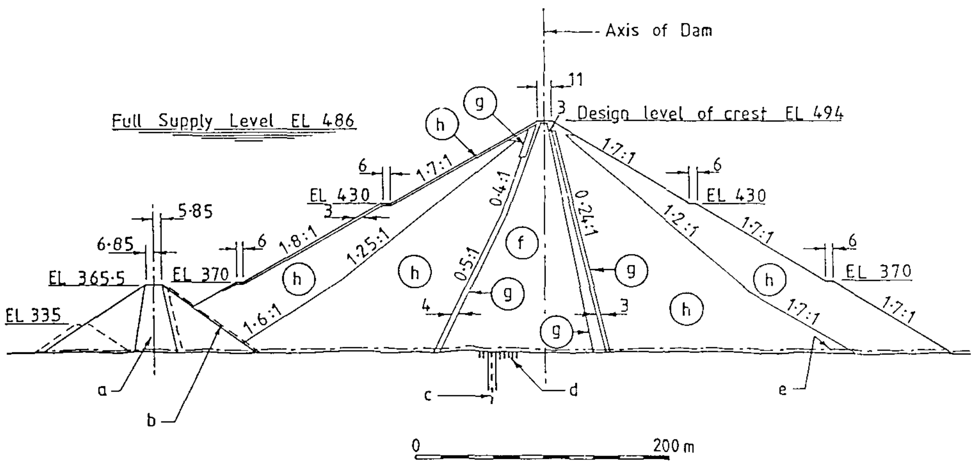


Fig. 1
Maximum section of Dartmouth Dam

a. Cofferdam
b. Mesh
c. Grout Curtain
d. Blanket Grouting
e. Ground Line
f. Core
g. Filters
h. Rockfill

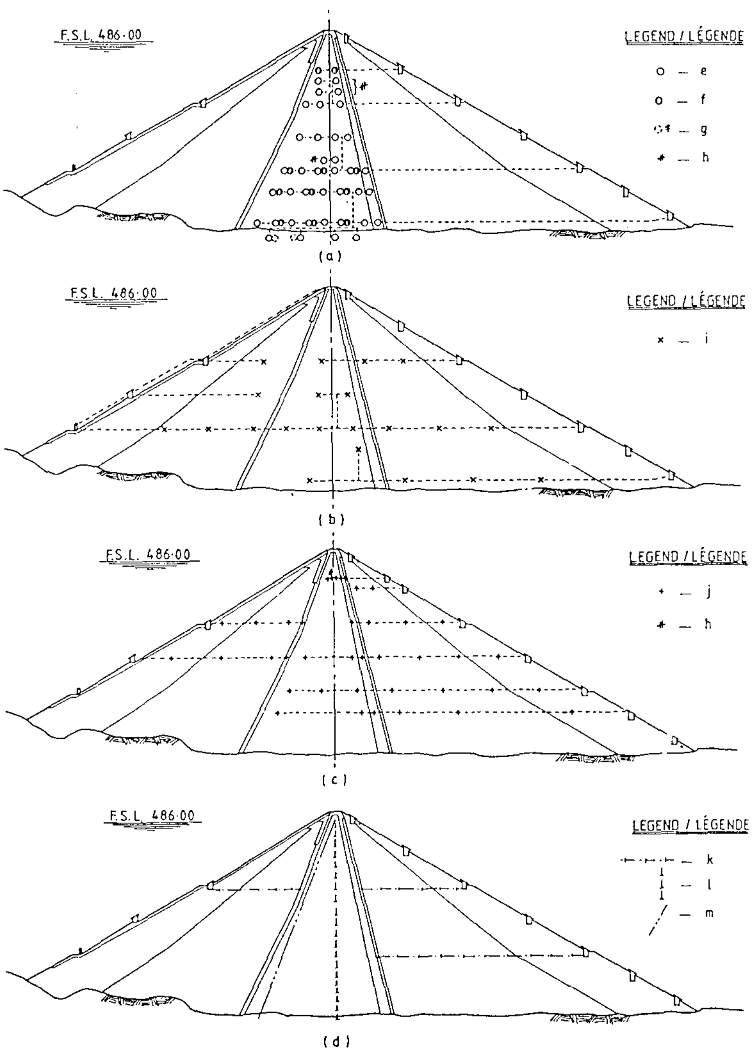


Fig. 2
Instruments on Maximum Section

a. Piezometers
b. Pressure Cell Groups
c. Hydrostatic Settlement Gauges
d. Movement Indicators
e. Hydraulic Piezometers
f. Diaphragm Piezometers
g. Piezometer located slightly off section
h. Additional Instrumentation
i. Pressure Cell Group
j. Hydrostatic Settlement Device
k. Horizontal Movement
l. Vertical Settlement Installation
m. Slope Indicator

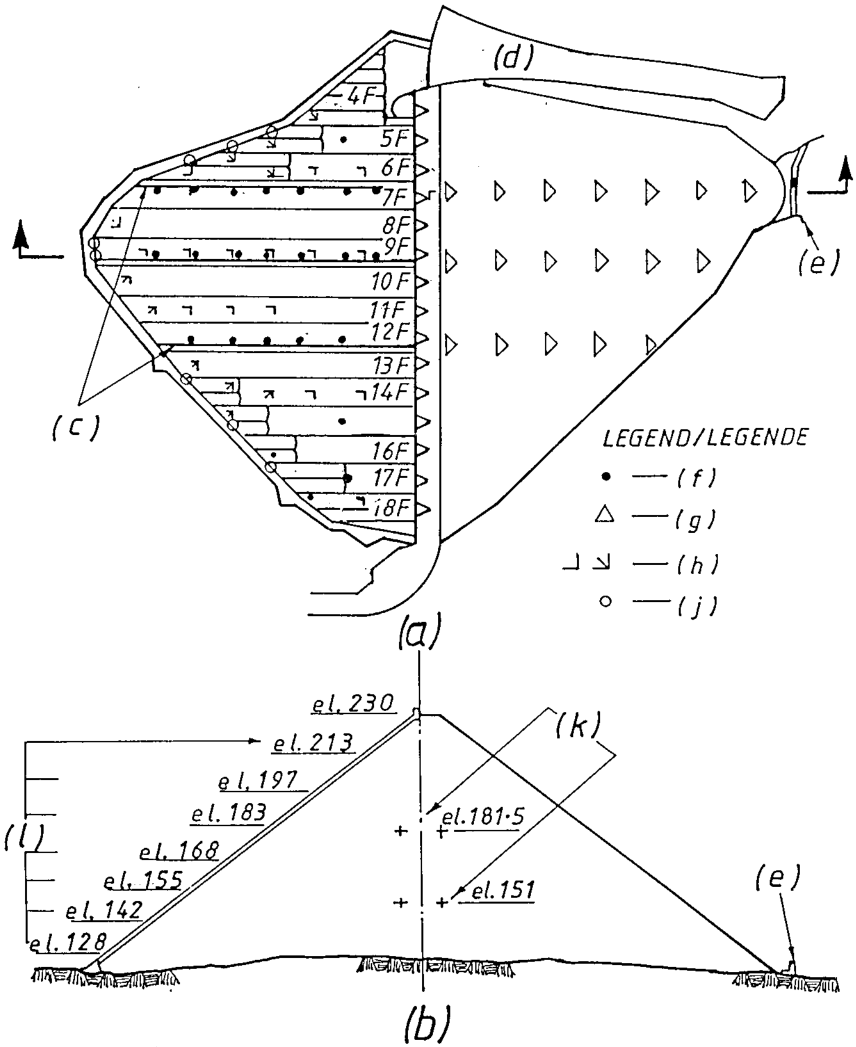


FIGURE 3:- General Arrangement of Instrumentation at Cethana Dam

(a) Plan View
(b) Cross Section
(c) Inclinometer Pipes
(d) Spillway
(e) Leakage Weir
(f) Anchor Points for Wires
(g) Survey Targets
(h) Strain Gauges
(j) Perimetric Joint Meters
(k) Hydrostatic Settlement Cell
(l) Installation Level of Strain Gauges

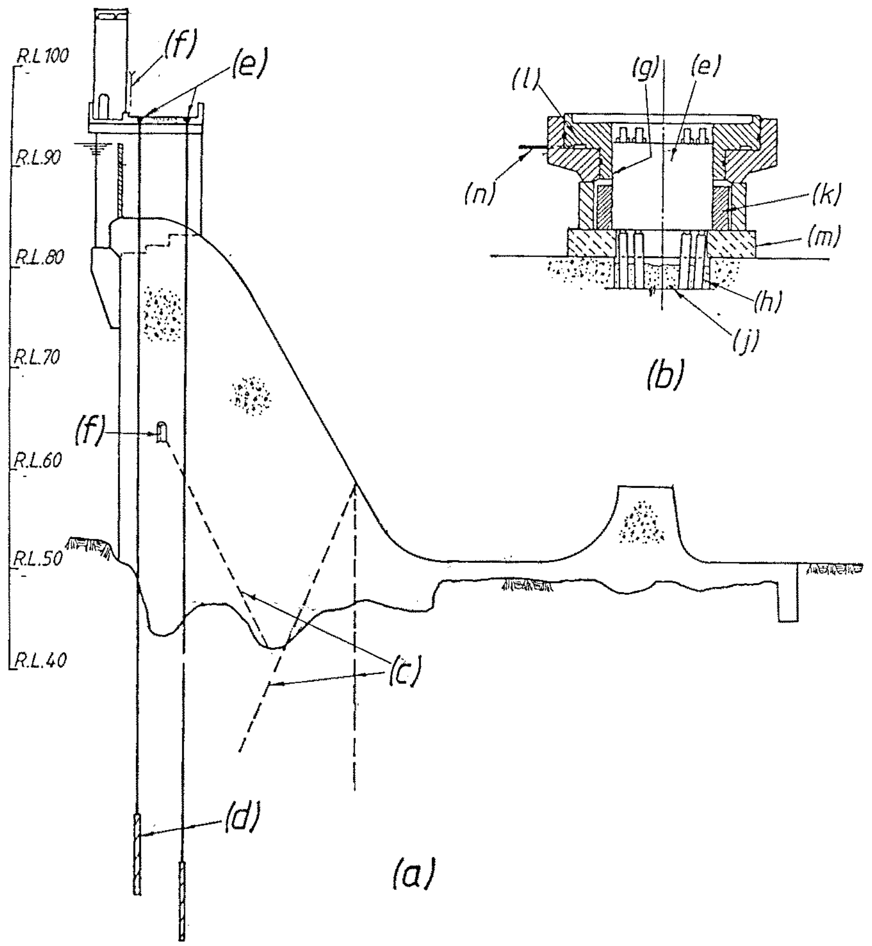


FIGURE 4 :-Details of Remedial Measures and Instrumentation: Hume Dam.

(a) Cross Section

(b) Detail of Load Monitoring for Cables

(c) Drainage holes at 6m.cts. (selected holes used for uplift pressure monitoring by down the hole hydraulic piezometers.

(d) 9000 kN-55 strand load monitorable post tensioning cables

(e) Post tensioning cable head

(f) Clinometers

(g) Cable head threaded to take load cell

(h) 15·2 mm dia strands sheathed in grease filled tubes

(j) Grout

(k) Ring nut

(l) Hydraulic load cell

(m) Bearing Plate

(n) Hydraulic line to Pump

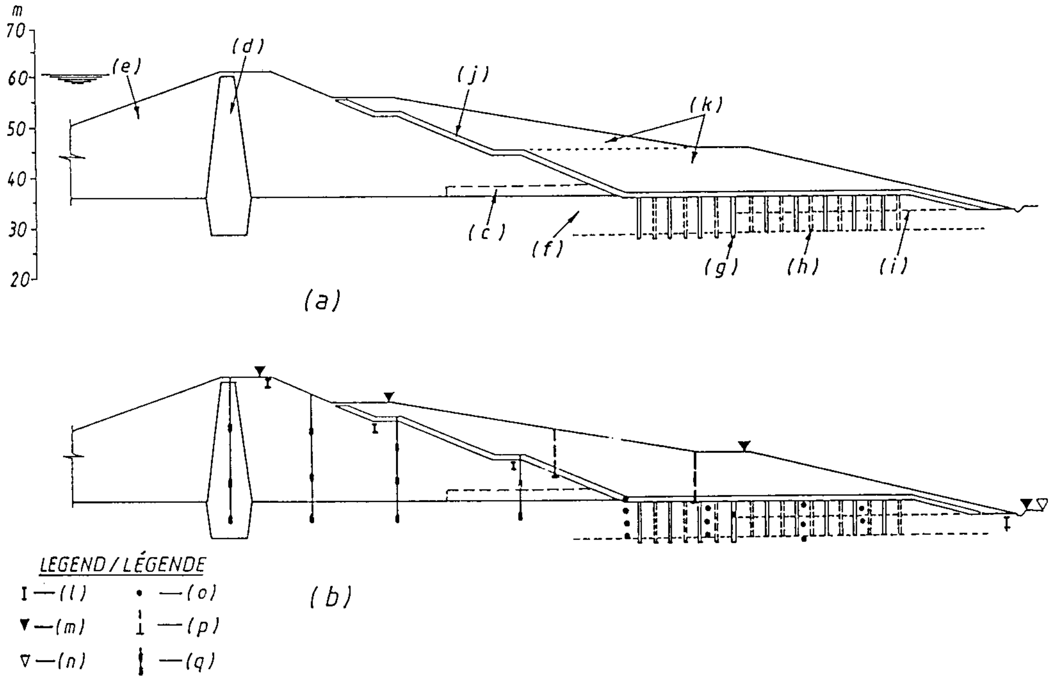


Figure 5 PROSPECT DAM - REMEDIAL MEASURES AND MONITORING SYSTEMS

(a)	Cross section showing old dam and fill buttressing
(b)	Cross section showing monitoring systems
(c)	Rubble filled drainage tunnel
(d)	Puddle clay core
(e)	Clay shoulders
(f)	Alluvial clay foundation
(g)	Filter drainage cutoff trench along downstream foundation. Extending to rock
(h)	Vertical sand drains
(i)	Lateral drains
(j)	Filter zone
(k)	Stabilizing fill material (shale) constructed in two stages
(l)	Inclinometers
(m)	Surface settlement points
(n)	Seepage collection and measurement
(o)	Pneumatic and electric piezometers
(p)	Foundation settlement installations
(q)	Open standpipe piezometers

Appendix B
Annexe B

REPORT BY THE AUSTRIAN NATIONAL COMMITTEE

GENERAL CONSIDERATIONS

The safety of a dam does not only depend on the quality of design and construction, but also on that of maintenance and monitoring during the whole period of operation. In order to assess the condition of a dam an adequately designed and maintained monitoring system is required that takes account of the specific type and condition of the individual dam and produces accurate data on dam behaviour. Dam supervision has to refer to three main aspects:

- Operational facilities:
  It is a matter of fact that the continuous availability of operational facilities must be assured by means of careful maintenance and checked whenever deemed necessary. This applies in particular to flood discharge at full reservoir before the period of floods expected to occur according to experience. As soon as dimensions, efficiency or reliability of any flood discharge facilities are deemed insufficient on the basis of experience previously gained in-situ, appropriate countermeasures must be taken.
- Visual inspection:
  Visual inspection of the dam itself, reservoir slopes and downstream area in the form of periodic checks in-situ is of primary importance. A general plan (supplemented by detail plans if necessary) including all characteristic features, such as survey points, springs, areas exposed to sliding for reservoir slopes and downstream area, cracks and seepage areas of the dam body should underly these inspections. Photos may be a valuable contribution to documentation.
- Monitoring:
  In general, monitoring serves two purposes:
  Check of the design parameters, often required during the first years of operation.
  Check of the behaviour of the dam at some representative points throughout the whole period of operation.

The following considerations will focus on measurement of changes occurring during dam operation.

1. THE SAFETY CONDITIONS OF A DAM

1.1. Safety criteria

It is nearly impossible to quantify the safety factor of any dam. In connection with this problem it should be taken into account that a distinction must be made between normal dam operation and extraordinary events, such as earthquakes.
Expressed in a simplified manner, a dam can be considered to be safe, if

- relevant deformations of dam body and its foundation encountered during dam operation are in accordance with the calculated values and the increase of permanent deformations is dying away;
- an appropriate drainage system installed in dam body and its foundation proves evi-

dence of the envisaged degree of impermeability which is indicated by seepage measurements.

Numerous deformation measurements are usual since the beginning of dam construction. The design has to include also an effective drainage system to be emplaced in dam body and its foundation so as to control seepage paths for any dam type. This system is of particular importance for the body of fill dams, since it allows detection of permeable areas and thus eliminates the risk of internal erosion.

1.2. Organisation of dam surveillance

Any owner of any dam in Austria has the obligation to nominate a dam operator and notify the authority in charge of dam surveillance. The dam operator is responsible to the authority for

- assuring maintenance of dam, appurtenant structures and monitoring system,
- checking the continuous evaluation of the readings,
- compiling the annual reports prepared for the authority,
- informing the dam supervisor in charge appointed by the relevant provincial government in the case of extraordinary events,
- providing for, if necessary, warning of the inhabitants concerned.

The authority in charge of dam surveillance has to check the annual reports and to inspect each dam at five years intervals. Specialists in charge of the individual safety aspects under study will also assist to the inspection.

2. PHYSICAL QUANTITIES AND INSTRUMENTS

2.1. Applicable to any type of dam

It is for operational reasons alone that, for any dam, the reservoir level is continuously measured and remotely transmitted to the control centre of the power station. Meteorological stations were installed near a great number of dams to measure rainfall, ambient temperature, wind speed etc. Wherever local conditions make it necessary, rainfall and flow measuring stations in the catchment area enable adequate measures to be taken in due time to cope with flood waves and to provide for a safe discharge.

Continuous seepage measurements constitute a main part of monitoring of any dam type for serious cracks in concrete dams due to unadmissible deformations cause a rapid increase of seepage; similarly enables a controlled drain layer downstream the watertight membrane or core of an embankment dam to detect very early impermeabilities, which may cause serious inner erosions. Reliability of these measurements depends, however, on a drainage system installed in both dam body and its foundation that is optimally adapted to the conditions prevailing. Flow measurements constitute overall measurements and cover the whole structure, provided that the system has been adequately arranged. Depending on the dam heigth measurement sections are appropriate to early detect possible permeabilities and to increase accuracy. For higher amounts of seepage, measurement of suspended matter is also advisable.

Efficiency of drainage system emplaced in the dam foundation is checked by measurements of uplift and interstitial pressures. With a correctly arranged and safely operating drainage system excessive uplift and pressures in clefts can be avoided over large areas (only over large areas these pressures can sum up to significant forces).

At least once a year and also after extreme rainfalls and strong earthquakes the reservoir slopes should be inspected in-situ. A geologist who is familiar with the local conditions should form part of the inspecting team. Any change, particularly any sign of major landslides has to be investigated. In areas exposed to potential landslides geodetic measurements must be performed periodically.

2.2. Concrete dams

The aggressive character of the storage water may negatively affect the durability of the dam concrete so that chemical analysis of the storage water proves advisable at tions to calculate deformations.

Stress and strain measurements, as well as measurements of the deformation modulus of concrete are somewhat problematic. They would produce valuable data as compared with those obtained from calculations. Nevertheless they call for further development work on the mode of realization.

2.3. Fill dams

In addition to the measurements pointed out in item 2.1. there are short- and long-term safety aspects that appear only from information on load bearing capacity. Special emphasis must be placed on checks of fundamentals and results of the calculations performed and on an early detection of irregularities in dam behaviour. Measurements of deformation, strain, earth pressure, stress, ground water pressure and pore pressure, seismic observations and special measurements possibly required in individual cases are integral parts of dam monitoring.

Deformation measurements carried out by means of triangulation of points at the dam crest and at the slopes are the most frequent ones, because these are easy and furnish reliable quantitative information on dam behaviour already in the first stage of measuring.

To determine the deformations in the interior of the dam - a procedure which is rather complicated - it is necessary already during construction of the embankment to emplace adequate measuring instruments. A special level indicating equipment that was developed in Austria and is common practice today has proved especially successful. The instruments used are displaceable metal plates that are threaded on tubes and connected with the dam fill material. These plates are localized by means of induction cells and their location is determined by clinometers and hose balances.

The tubes may be inclined either vertically or horizontally. For uni-axial or local deformation measurements stationary hose balances, extensometer gauge lengths and radially arranged groups of extensometers are used.

To fulfill high accuracy and reliability requirements plumb line sets have also been emplaced, wherever deemed necessary. These devices are installed usually in shafts that were erected synchronously with the construction of the dam body. Furthermore, the shaft which is man-sized for functional reasons, allows accurate deformation control of specially selected points and arreas and facilitates emplacement of measuring lines and pipes extending from the various measuring horizons to the central measuring chamber.

Deformation measurements performed on fill dams generally yielded good results, whereas measurements of earth pressure and stress give rise to problems on account of the differing deformation properties of the emplaced plates and fill material, as well as on the resulting disturbance of the stress conditions. Since stress transfer is frequently encountered in zoned fill dams due to the differing requirements and physical properties of the fill materials and thus considerably influences deformations, earth and pore pressures, almost any high fill dam is provided with this type of equipment. Adequate gauging methods also contribute to improve the quality of the readings.

Piezometer measurements in the rock foundation are carried out only in special cases in order to determine the relief of the water pressure along short seepage paths and to check the performance of foundation sealing or relevant uplift in concrete structures.

Determinations of the thermal conditions prevailing within the embankment revealed to be appropriate for dams situated at high altitudes, whose mean annual temperatures range around 0° C and whose filling and sealing materials are susceptible to frost.

3. MEASUREMENT SYSTEMS FOR STATIC CHECK-UP

The measuring points and parameters for the purpose of dam monitoring during the first filling periods should be selected so as to allow a direct comparison with assumptions and results of calculations. Therefore, the equipment must cover those cross-sections and points of the structure the stability calculations were based on.

In the case of fill dams the development of pore pressure of the fill material must be observed, whenever cohesive fill material is used or foundation is overlained by cohesive material. Evaluation of the data obtained from measurements must be done during construction with a view to dam safety, and as soon as the capability of pore pressure relief decreases and in the case of rapid draw-down of the reservoir head.

Additional measurements must be made in areas in which reconnaissance work performed during construction has revealed conditions that differ from those underlying the design assumptions. Need for other additional measurements may result from the experience gained during the first filling periods. Furthermore, additional measurements may prove necessary in the case of an unexpected behaviour of a dam, its foundation or the reservoir slopes.

Selection of data for remote transmission and automation is based on the aspects described under item 2 and the experiences gained during the first filling periods. Any measurements, however, must be carried out in-situ from time to time, so as to allow a check of the remotely transmitted values.

4. CHECK SYSTEM FOR SEISMIC SURVEILLANCE

On account of the low seismicity in the areas of the Austrian dams only a few dams were equipped with micro-seismic instruments (either in the close vicinity of the structure or at the dam base) and with instruments of lower sensitivity at the dam crest.

Vibration tests carried out at several dams proved evidence with results of analysis for the first natural frequences and the damping factors.

5. READ-OUT FREQUENCIES

ICOLD Bulletin 41 provides valuable fundamentals on the frequency of measurements during the various construction and operation stages of a dam that are also in good coincidence with the measuring intervals commonly practiced in Austria. Special conditions, however, may require other intervals to be adopted.

6. AUTOMATIZATION OF THE MEASURING SYSTEM

The need for remote monitoring resulted from both the call for permanent monitoring throughout the year of a large number of Austrian dams situated far off any permanent settlement and the difficulty arising from the lack of reliable personnel that is willing to work in shifts. The application of methods from the fields of teletransmission and computer technology that have made great progress over the past few decades not only helped intensify continuous monitoring but also save cost due to the short amortization time as a consequence of a reduced number of employees.

A general report on monitoring of the Austrian dams was presented as early as 1977 by Petzny. The present standard of remote monitoring of the Austrian dams will appear from the following tables in which a distinction has been made between concrete dams (arch and gravity dams) and fill dams. (Annex 1 - 3)

For data which had not been included in the automated telemonitoring system a portable electronic data processing system has been specially developed recently. This system consists in data storage on floppy disks with a scanner and subsequent treatment by the central computer.

In the past, continuous check even of the main data was fairly limited. The progress made in the field of technical data processing enables now continuous computation of the data required for an adequate evaluation from the base readings, but also

- automatic checks of system and reasonableness,
- prompt comparison of actual and calculated values, and
- gradient observation.

Applying this type of data control which also includes performance monitoring of measuring and transmission systems enables the dam operator to analyse, without any longer intervals.

Air and water temperatures gain in importance for appraisal of deformation behaviour, specially at slim arch dams of moderate height. For this reason measurement of profiles of water temperature covering the whole dam height during all the four seasons suggests itself. Continuous recording of ambient temperature values is common practice.

In case of gravity dams with non-grouted vertical block joints, the displacements should be monitored in every single block. For this type of dam measurement of displacements at the crest performed with vertical plumb lines in combination with displacement measurements at the block joints or with geodetic measurements are believed to be sufficient, since every displacement within the dam base area is reflected at the dam crest, at least in the same order of magnitude.

In case of monolithic dams - gravity dams with grouted block joints or arch dams - there is no doubt that the displacement of the crest is of importance when assessing the longtime behaviour of the dam. Knowledge of the displacements only at the crest is certainly not sufficient to allow assessment of the behaviour of dam and its foundation for the time being, because local zones of weakness within dam body or within dam foundation are largely neutralized by the whole dam body through force transfer and will hardly ever affect crest displacement at an early stage.

Since potential failures start more frequently from the foundation, deformation measurements performed near the dam base area are more likely to be decisive for the assessment of dam safety. However, major deformations of the foundation in most cases are accompanied by increasing seepage, a fact which underlines the importance of seepage measurements in the foundation, too.

On account of high accuracy and easy handling plumb line sets have proved mostly satisfactory for measurement of horizontal and tangential displacements (inverted plumb lines for dam foundation, inverted plumb lines or plumbs for dam body). The drill holes may also accommodate invar wires to measure vertical displacements.

For slim dams with vertical curvature, where pendulums cannot be arranged, clinometer chains along vertical sections enable the calculation of the flexural line and the crest displacement. Laserplumb lines enable the measurement of displacements in inclined shafts (chapter 10).

Rod extensometers have proved most suitable for measurements within the foundation. If greater gauge lengths are required these rods are roller seated. On account of safe construction and the relatively low cost involved for short drill holes extensometers covering several gauge lengths each were replaced in many cases by separate extensometers for each length. In recent times sliding micro-meters have proved appropriate to localize longitudinal deformation of concrete and rock along the borehole.

These measuring methods only yield relative deformations values, whereas clinometer measurements produce absolute values of deformation. Changes in rotations about tangential axis should be measured, in particular, at dam base, preferably at three points (near upstream face, in centre and near downstream face) of a cross-section so as to permit measurement of any distortion possibly occurring of the cross-section.

Absolute displacements can be determined by means of geodetic measurements performed with utmost accuracy. Alignment surveys are suitable for non-curved gravity dams, whereas traverses are appropriate for arch dams. The plumb line sets should be integrated into these measuring chains as far as possible. Levelling at crest and/or inspection galleries should also include the before-mentioned invar wire sets. Measurements of the distance between the valley slopes may furnish supplementary information.

In case of dams with block joints to be grouted measurement of the joint widths should begin at an early stage and continue in an intensified manner during block joint grouting. In general, measurements of this kind are believed not to be necessary during future operation, whereas monitoring of crack opening is required throughout the whole service period. Acoustic emission method has proved successful for early detection and localization of cracks. It is, however, rather complicated and involves high cost due to the small range of operation of the instruments used. Record interpretation is difficult and reserved for specialists.

Temperature measurements of the dam concrete are required for selected cross-sec-further comparison of the readings that is lengthy and must be done manually, the causes of unusual changes in the values before deciding upon the measures to be taken.

If the measurements exceed the allowable limits, a visual or acoustic sign is first given to the operating personnel in the control centre of the power station. These persons arrange for printing out of all readings of the preceding period and for notification of the staff in charge of the measuring system. If this check which has to be performed within a short time does indeed prove evidence of unusual tendencies, the dam operator is informed and an inspection in-situ is made to which other specialists in charge may also assist.

The inhabitants downstream of the dam are warned by the public authorities only after the dam operator has checked the conditions actually prevailing within the framework of the inspection in-situ. Fully automatic alarm release is not deemed desirable, bearing in mind the risk of false alarm. Moreover, a correctly designed measuring system would detect unfavourable changes at an early stage.

7. DATA EVALUATION

All readings may be chronologically stored and must be complemented by manually obtained data. This assures that for each dam a data bank is available which allows statistic evaluation of any reading after several years of operation.

During the first filling periods only deterministic models offer the possibility of comparing the measured values with the calculated values underlying the design. It is, however, possible to verify the assumptions made in the deterministic model by means of measurements already during first reservoir filling so that the assumptions made can be adapted to the conditions actually prevailing. This means that actually a hybrid model is used.

After several filling periods the desired values can be determined by means of a statistic-based mathematical model called multiple linear regression analysis. In this context one specific method has proved satisfactory which uses only two parameters that are expected to be available for any dam in order to quantify the external influences, viz. reservoir level and ambient temperature. By the way, this method is useful not only when determining deformation, but also for the interpretation of any other measurement.

The results from these regression analyses permit to determine improved parameters for the deterministic model as well as the allowable range of variation of the measured values and to identify possible long-term developments of changes in the measured values. Assessment of these analyses must be made by specialists in statistics together with dam experts.

8. IN SERVICE DAMS WITHOUT A SUFFICIENT MONITORING SYSTEM

The monitoring systems of older dams may prove outmoded and call for updating according to today's standards, although they were in accordance with the standards applicable at the time of installation. Updating may be confined to the data referring to safety control as specified under item 1.1. Since most of the dams concerned are small, permeability checks of dam and its foundation and regular inspections in-situ could possibly be sufficient. It seems, however, not reasonable to specify guidelines that are generally applicable.

9. CHECK-UP UNDER SPECIAL CONDITIONS

No additional remarks.

10. NEW TYPES OF MEASUREMENT

10.1. Acoustic emission

A measuring system based on acoustic emission allows registration of acoustic waves that occur during crack formation in concrete or rock masses. Seismology-based measuring systems are suitable to measure cracks beyond 1 000 m length and frequencies lower than 1 Hz, whereas systems using acoustic emission are able to register cracks of 0,1 to 1 m length with frequencies ranging from 1 to 10 kHz. This fact is made use of to detect any sign of imminent dam cracks.

The acoustic emmission-based system allows to obtain information as to how many and how often microfractures take place and on the intensity of the acoustic waves. Several acoustic pick-ups make it possible to conclude on the potential place of fracturing. On account of the fact that sounds are not only emitted as a consequence of dam cracks, but also of other physical phenomena, such as friction noise and turbulent flow, it is important to carefully evaluate the readings and to contrast them with the values obtained from deformation and stress measurements so as to facilitate further interpretation.

A seismo-acoustic plant of this type was arranged at Kölnbrein arch dam and shall be schematically presented in Fig. 1.

10.2. Laser plumb line

The use of a directed monochromatic light ray by means of a laser tube constitutes the first serious alternative to the wire plumb lines that have been used up to now for even in inclined shafts. It must, however, be borne in mind that the laser beam obeys the same physical laws than does ordinary light (e.g. refractions). During assembly of the system distortions occurring in the vicinity of transmitter and receiver must be taken into account. As far as evaluation of readings taken in systems with inclined areas is concerned, the influences of the general displacements vectors must also be taken into consideration. Another substantial advantage this system affords is that remote signal transmission does not involve any additional equipment as is the case with traditional plumb line system.

This optic laser plumb line is installed at Zillergründl arch dam between the crest and the topmost control gallery. (Fig. 2)

10.3. Magnetic measuring device for asphaltic concrete core wall deformations

The deformation behaviour of asphaltic concrete core walls under varying load conditions in high dams has a considerable aspect and influence on the imperviousness of the material. So far information obtained in laboratory has not been confirmed in practice. Therefore a new magnetic measuring device was developed, connected to either side of the core wall, to monitor the variations of thickness during impounding. This consists of two strong permanent magnets. The magnetic field created by them permeates the asphaltic concrete. Thickness variations of the core are reflected by variations in the magnetic field and can thus be measured with an accuracy of tenths of millimeters by a sensor installed on the downstream side between core wall and magnet (Fig. 3). All parts of this measuring device are accomodated in two watertight non magnetic pipes.

Figure 4 shows thickness variations to the completion of construction and operation. The disproportionate high widening of the core wall during the first impounding is reduced to deformation mechanism of the asphaltic concrete. As expected on further investigations the movements quickly decreased and didn't influence seepage of the dam.

10.4. Automatization of in-situ measurement

For in-situ measurements of not automatically recorded data a system using an intelligent hand held computer has been developed:
- the code of the instrument is read by a bar scanner,
- the measured value is put in by the keyboard.

The data stored are transferred to a host computer, which
- calculates the desired value,
- makes a control of plausibility and

- stores the checked data in a data file that allows future evaluation.

Applying this method the way from the in-situ measurement to the data file is highly simplified and thus the possibility of errors is reduced considerably.

11. AUTHORITY AND SAFETY CONTROL

See 1.2.

12. MEANINGFUL EXAMPLES

12.1. Concrete gravity dam

The New Tauernmoos gravity dam is 1 100 m long at the crest and includes 69 concrete blocks. It is situated on a natural rock barrier which was not impounded before. The dam has a maximum height of 53 m and a concrete volume of 250 000 m^3 and was put into operation in 1973. The present report will be confined to the method of determining the displacement of each dam block.

In contrast to monolithic arch dams potential small-scale displacements of gravity dams with non-grouted block joints do not necessarily affect even the neighbouring blocks. In order to assure complete safety control, it would be necessary to observe each of the blocks. This requirement can, however, not be fulfilled by means of the devices generally used, such as plumb lines, extensometers and clinometers.

Control of width and relative displacements (i.e. threedimensional) of all block joints in conjunction with current deformation measurements taken at selected "measuring blocks", however, come very close to the claim of complete safety control of a gravity dam. The dam blocks located between the selected "measuring blocks" are connected with one another by means of a "signal chain" (a chain of limit value indicators arranged at the block joints). These indicators (cf. Fig. 5) constitute a simple and economical method of remote control and form several sections of signalization. The most appropriate and promising location of such indicators is at the dam crest.

Deviations from normal conditions in the foundation area (hazardous events often start from the dam base) appear more distinctly at the crest than at the bottom. The limit value indicators are intended to react even to slight relative displacements and release signals at the relevant panel in the control centre.

The remote control system consists of constant-set limitvalue indicators that are independent of measurement transducers with a very narrow range, and of the relevant indicating panels in the control centre. Since gravity dams of moderate height usually do not undergo major deformations and exhibit rather low amounts of seepage, safety control with groups of signals seems appropriate and economical. For reasons of operational reliability these limit value indicators are of a simple and solid design.

The limit value control unit comprises:

- limit value readings (inductive proximity switches) obtaines at three inverted plumb line locations, which cover the crest deformations towards downstream and
- two extensometer locations (inductive proximity switches),
- four signal chains comprising the limit values for joint measurement, arranged in the upper inspection gallery. 54 block joints are equipped with limit value indicators which form four groups of signals (for this purpose the dam was divided into four sections). The mechanically operating limit value indicators are set so as to give a signal as soon as any radial or vertical relative displacement at the block joint exceeds 2 mm or that the joint width exceeds the maximum amount depending on temperature action by approx. 1 mm (the annual variation in the joint widths is about 3 mm),
- five signal groups indicating seepage limit values; one for each of the four dam sections the fifth group includes seepage observation points at drainage galleries,
- seven seepage observation points in the lowermost inspection gallery and three of same in the drainage galleries out of the five groups are equipped with limit value indicators (float type switches),
- one threshold limit value covering the filling level.

Several typical local observation points (two radial crest deformations, ambient temperature and water level) are also equipped with remote measuring devices. These values are transmitted into the control centre and recorded there. Now assessment of the dam behaviour is possible even within the range of variation allowed for (e.g. in case of unforeseen events) and maximum values are obtained that could not be determined in the course of onsite measuring carried out every two weeks.

The computer integrated in the control centre receives the readings and signals that arrive via two ways of transmission, viz. a flood-proof directional radio link and a cableline. The reliability of transmission is improved by double transmission of each signal and evaluation by two computers that are independent of each other. Signals are put out only upon complete coincidence of the computer results. Values exceeding the limits joint form an "alarm signal" only if they complement each other in a reasonable manner (e.g. plumb line measurement and seepage measurement of the same dam section produce limit values) and if the filling level exceeds the given threshold value (even in the case of dam failure the downstream population is not exposed to danger as long as the threshold value is not reached). Visual and acoustic signals are indicated to the person in charge at the control centre (for operational reasons personnel is required to work around the clock) and a printer records these readings. The data indicated at panel are a valuable help to dam operator who must decide as to what kind of immediate precaution is to be taken, if any.

12.2. The measuring equipment of Zillergründl arch dam

Zillergründl arch dam, 186 m high, 520 m long at the crest, 1,37 million m³ of concrete volume, was concreted between 1983 and 1985. First reservoir filling was started in 1986. The measuring system and the equipment as such have been conceived with a view surements generally performed additional deformation measurements are intended to be carried out and are as follows.

- Movements of the reservoir slopes:
  Advanced geodetic instruments will be used to measure the distance between the valley slopes at a level higher than maximum filling level upstream and at several levels downstream of the dam. The measuring accuracy ranges from ± 1 mm over lengths from 500 m to 1 000 m.
- Movements of the fixed points of the plumb lines:
  Three plumb line sets (at the middle section and approximately at the quarter points of the dam) which are accomodated in shafts together with invar wire extensometers, measure the relative displacements of the points of reading in the three directions perpendicular to each other, related to their fixed points at 80 m and 60 m depth, respectively, below the dam base. To monitor possible movements of fixed points the points of the plumb lines at which readings are taken form part of a traverse and a levelling in the uppermost inspection gallery. Owing to five measuring windows the traverse in turn forms part of the downstream system of fixed reference points, thus providing absolute deformation values of the uppermost inspection gallery and also of the plumb line fixed points by means of the plumb lines and the invar wire extensometer. The accuracy expected is ± 1 mm.
- Rotations about the vertical axis:
  The movement of a point in space is determined by the displacements in the three directions perpendicular to each other and the rotations about these three axes. Two out of the three rotations (about the horizontal radial and tangential axis) are measured by adequately arranged clinometers. The rotations about the tangential axis may be derived also from vertical extensometer measurements carried out at dam heel and dam toe. The rotations about the radial axis are derived from the tangential displacements which are measured by the plumb lines or from levelling in the relevant inspection galleries. Rotations about the vertical axis, however, escape from clinometer measurements. For this reason horizontal tangential extensometers are located at several levels near the upstream and downstream dam faces. The difference in their longitudinal deformations and the distance between these extensometers supply infor-

mation on the rotations.

- Settlement of the rock foundation at mid-valley:
  In the three inspection galleries near the dam base (upstream grouting gallery in the apron, bottom inspection gallery in the upstream section of the dam, and inspection gallery at the downstream dam toe) the vertical displacements are measured by means of partly closed levelling loops which are connected with a fixed point located at the rock outside the dam downstream via a levelling in the drainage gallery. This levelling also covers all measuring heads of the vertical extensometers accomodated in these three galleries so that major movements of the extensometer anchorage points can be measured.
  The measurements were taken up at an early stage, shortly after the different galleries have been accessible.

12.3. Measurement of radial displacements of thin arch dams with clinometer measuring chain

The Moell arch dam of Glockner Kaprun hydro power system is 56 m high and has a crest length of 164 m. The thickness of the curved crown cantilever increases from 3 m at the crest to 7,5 m at the base. It is not within reach in winter time. A plumb line was not possible, therefore a clinometer chain was installed in grooves at the downstream surface of the crown cantilever (Fig.7). The measured variation of inclinations is equivalent to the tangents of the flexural line, thus enabling to calculate the radial displacements of the crown.

The installation of this electrical instruments gave the possibility to transfer the measured data to a computer in the central control station of the power plant, where these data were checked for plausibility and stored in the data bank together with the storage level and the air temperature.

After some years a regression analysis were performed to evaluate the influence of storage water and air temperature to the permanent as well as the elastic displacements of the crest. The quality of the results of this regression analysis is characterisized by the coefficient of correlation $R^2 = 0,985$ and the standard error of estimate $S = 3$ %.

Now it is possible to precast the displacement of the crest due to the actual storage water level and air temperature and to compare this value with the calculated value from the foregoing measurements. Exceeds the difference a settled value, a visual or acoustic sign is given to the operation staff, who arranges checking the measuring system and if necessary, an inspection in situ of the dam.

12.4. Finstertal rockfill dam

The Finstertal dam (constructed from 1977 to 1980) is remarkable for being at present the highest rockfill structure with an asphaltic concrete core wall. The somewhat unusual design requires intense monitoring of its behaviour by a generously conceived monitoring equipment.

In respect of its concept the monitoring system is designed so as to enable reliable appraisal of the condition of the dam at any time during construction and operation. The instruments are located at one principal and five secondary sections and at three different levels, with concentrated instrumentation of the zone immediately downstream of the inclined asphaltic concrete core wall (principal section, Fig. 8).
Therefore a considerable proportion of the installed devices and equipments, in particular the horizontal plate gauges and the plumb-line shaft (Fig. 9), were especially developed or modified for this project. The shaft affords access to the central part of the dam over its full height, allows precise monitoring of selected points by fluid level devices an extensometers and facilitates clear arrangement of all cables and pipelines from the various instrument horizons towards the measuring chamber.

Furthermore it is pointed to a new magnetic measuring device, tailored to investigations of the variations of thickness of the core wall (see chapter 10.3.).

Annex 1: Gravity dams

Number of "Large Dams in Austria", Vienna 1977	Name of the dam	Owner	Characteristic data		attainable all the year	Telemeasurement								Ultimate data control									Television
						Reservoir		Dam				Control center		adjustment									
									Water					constant			periodical			continuous			
															Water			Water			Water		
			Height	Reservoir capacity		Level	Air temperature	Displacements	Pressure	Quantity	Temperature of concrete	at the dam	powerhouse	Displacements	Pressure	Quantity	Displacements	Pressure	Quantity	Displacements	Pressure	Quantity	
			m	1 000 m³				Number															
6a	Spullersee-Süd	ÖBB	39	15 700	nein	●	●	1	12	1	-	-	●	1	-	1	-	-	-	-	-	-	-
6b	Spullersee-Nord	ÖBB	28					1	-	1	-	●	o	1	-	1	-	-	-	-	-	-	-
9	Vermunt	VIW	50	5 400		●	-	1	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-
13a	Silvretta	VIW	80	39 100	ja	●	-	1	-	o	-	●	-	-	-	-	1	-	-	-	-	-	-
21b	Margaritze	TKW	40	3 200	nein	●	●	3	-	1	3	-	●	-	-	-	-	-	-	1	-	1	o
24	Weißsee	ÖBB	38	16 000	ja	●	-	1	-	-	-	-	●	3	-	2	-	-	-	-	-	-	-
26a	Mooser	TKW	107	85 000	ja	●	●	5	-	2	-	-	●	5	-	2	-	-	-	5	-	2	●
29	Großer Mühldorfersee	ÖDK	46,5	7 700	ja	●	●	1	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-
30	Kleiner Mühldorfersee	ÖDK	41	2 800	ja	●	●	1	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-
31	Hochalm	ÖDK	24,5	4 100	nein	●	●	-	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-
33	Lünersee	VIW	28	94 100	ja	●	-	1	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-
35	Amer	ÖBB	31	5 500	ja	●	-	1	-	-	-	-	●	1	-	1	-	-	-	-	-	-	-
41	Raggal	VKW	48	2 400	ja	●	●	5	-	-	-	-	●	-	-	-	(5)	-	-	-	-	-	-
46	Tauernmoos	ÖBB	53	55 300	ja	●	●	2	-	-	-	-	●	8	-	5	-	-	-	-	-	-	-

Annex 2: Arch dams

Number of "Large Dams in Austria", Vienna 1977	Name of the dam	Owner	Characteristic data		attainable all the year	Telemeasurement								Ultimate data control									Television
						Reservoir		Dam				Control center		adjustment									
														constant			periodical			continuous			
									Water						Water			Water			Water		
			Height	Reservoir capacity		Level	Air temperature	Displacements	Pressure	Quantity	Temperature of concrete	at the dam	powerhouse	Displacements	Pressure	Quantity	Displacements	Pressure	Quantity	Displacements	Pressure	Quantity	
			m	1 000 m³				Number															
12	Gerlos	TKW	39	700	ja	●	●	5	-	-	-	●	o	(5)	-	-	-	-	-	-	-	-	-
15	Salza	STEWEAG	52	11 000	ja	●	-	1	-	-	1	-	●	1	-	-	-	-	-	-	-	-	-
17	Hierzmann	STEWEAG	58	7 600	ja	●	-	1	-	-	1	-	●	1	-	-	-	-	-	-	-	-	-
18	Ranna	OKA	45	2 350	ja	●	●	1	-	-	1	-	●	1	-	-	-	-	-	-	-	-	-
19	Limberg	TKW	120	83 000	ja	●	●	3	-	2	-	-	●	3	-	2	-	-	-	3	-	2	●
21a	Möll	TKW	93	3 200	nein	●	●	5	-	-	5	-	●	-	-	-	-	-	-	1	-	-	o
22	Dobra	NEWAG	52	21 000	ja	●	-	2	-	-	-	-	●	-	-	-	2	-	-	-	-	-	-
26b	Drossen	TKW	112	85 000	ja	●	●	2	-	2	-	-	●	2	-	2	-	-	-	1	-	2	●
27	Ottenstein	NEWAG	69	73 000	ja	●	-	2	-	-	-	-	●	-	-	-	2	-	-	-	-	-	-
38	Kops	VIW	120	44 500	ja	●	●	5	-	o	(106)	●	-	-	-	-	1	-	-	-	-	-	-
43	Schlegeis	TKW	131	127 000	nein	●	●	17	12	3	6	-	●	1	-	3	11	-	-	(11)	-	(3)	●
50	Klaus	EKW	55	12 600	ja	●	●	1	-	1	1	●	●	1	-	1	-	-	-	-	-	-	-
54	Kölnbrein	ÖDK	200	200 000	nein	●	●	104	147	10	63	●	●	-	-	-	o	o	o	-	-	-	-
55	Sölk	STEWEAG	39	1 700	ja	●	-	1	-	-	2	-	●	-	-	-	-	-	-	(1)	-	-	-
25	Wiederschwing	KELAG	30	1 150	ja	●	o	1	-	-	-	-	o	(1)	-	-	-	-	-	-	-	-	-

Annex 3: Embankment Dams

Number of "Large Dams in Austria", Vienna 1977	Name of the dam	Owner	Characteristic data		attainable all the year	Telemeasurement							Ultimate data control									Television
						Reservoir		Dam			Control center		adjustment									
									Water				constant			periodical			continuous			
														Water			Water			Water		
			Height	Reservoir capacity		Level	Air temperature	Displacements	Pressure	Quantity	at the dam	powerhouse	Displacements	Pressure	Quantity	Displacements	Pressure	Quantity	Displacements	Pressure	Quantity	
			m	1 000 m³				Number														
3	Gosau	OKA	17	24 700	ja	●	-	-	-	1	-	●	1	-	-	-	-	-	-	-	-	-
16	Hollersbach	SAFE	16	135	ja	●	-	-	-	1	-	●	-	-	1	-	-	-	-	-	-	-
28	Rotgüldensee	SAFE	18	3 000	nein	●	-	-	-	1	-	●	-	-	1	-	-	-	-	-	-	-
37	Freibach	KELAG	41	5 500	ja	●	-	-	-	2	-	●	-	-	2	-	-	-	-	-	-	-
39	Gepatsch	TIWAG	153	138 000	ja	●	●	-	-	1	-	●	-	-	1	-	-	-	-	-	-	o
40	Dießbach	SAFE	36	4 800	nein	●	-	-	-	2	-	●	-	-	2	-	-	-	-	-	-	-
42	Durlaßboden	TKW	83	52 000	ja	●	●	1	-	2	o	●	9	-	2	4	-	-	-	-	-	o
44	Eberlaste	TKW	28	6 900	nein	●	●	-	7	10	-	●	-	-	-	-	7	10	-	-	-	●
45	Wurten	KELAG	42	2 800	ja	●	-	-	-	1	-	o	-	-	1	-	-	-	-	-	1	-
48	Galgenbichl	ÖDK	53	4 400	nein	●	-	-	-	1	-	●	-	-	1	-	-	-	-	-	-	-
49	Oschenikssee	KELAG	81	33 000	nein	●	-	-	-	1	-	o	-	-	1	-	-	-	-	-	1	-
51	Großsee	KELAG	57	13 300	nein	●	-	-	-	1	-	o	-	-	1	-	-	-	-	-	1	-
52	Hochwurten	KELAG	55	12 700	nein	●	-	-	-	1	-	o	-	-	1	-	-	-	-	-	1	-
53	Gößkar	ÖDK	57	1 800	nein	●	-	-	-	1	-	●	-	-	1	-	-	-	-	-	-	-
56	Längental	TIWAG	42	3 000	ja	●	●	-	-	1	-	●	-	-	1	-	-	-	-	-	-	●
57	Finstertal	TIWAG	149	60 000	ja	●	●	4	-	2	-	●	4	-	2	-	-	-	-	-	-	●
58	Bolgenach	VKW	92	8 350	ja	●	●	-	-	2	-	●	-	-	(2)	-	-	-	-	-	-	-
59	Bockhartsee	SAFE	33	14 000	nein	●	-	-	-	1	-	●	-	-	1	-	-	-	-	-	-	-
	Zirmsee	KELAG	44	8 700	nein	●	-	-	-	2	-	o	-	-	2	-	-	-	-	-	1	-

Fig. 1: Acoustic emission system at Kölnbrein arch dam

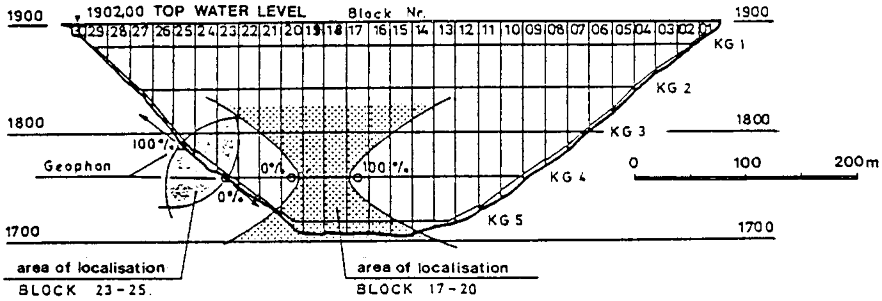


Fig. 3: Magnetic measuring device for core wall deformations

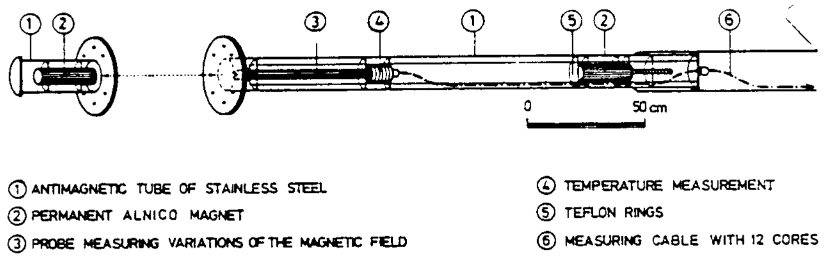
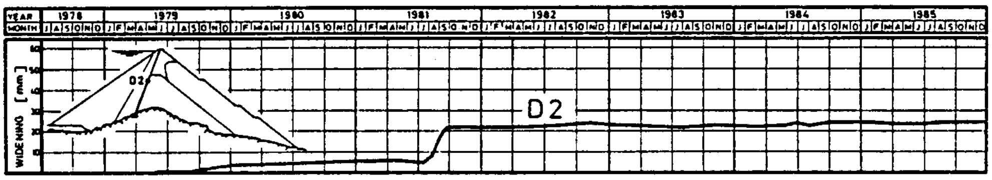


Fig. 4: Measurements of core wall thickness variations (deformation point D2)

Widening of core wall versus time



Progress of embankment construction and impounding

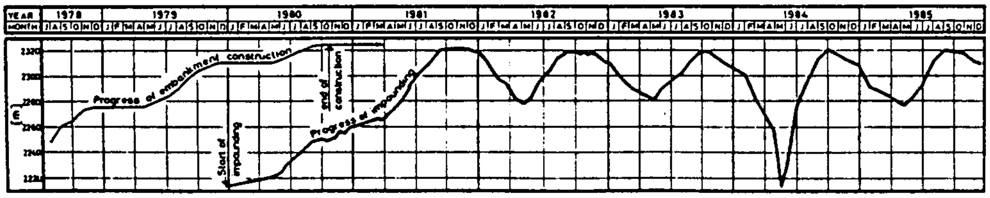


Fig. 2: Laser plumb line

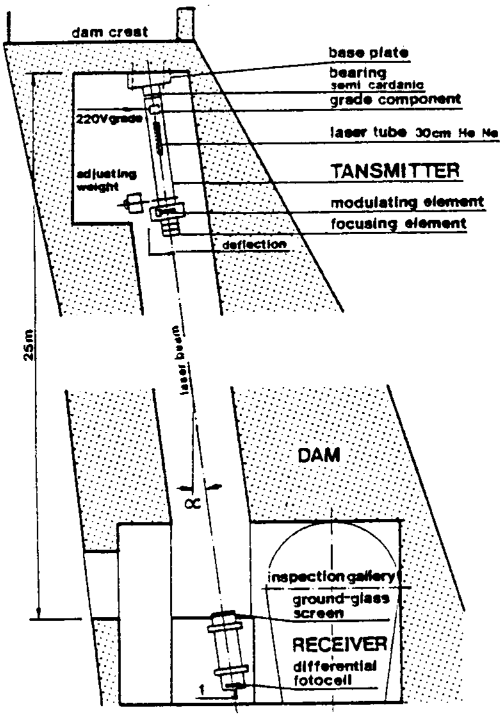


Fig. 6: Zillergründl arch dam, typical section with installations for measurement of deformations and waterpressure below the dam

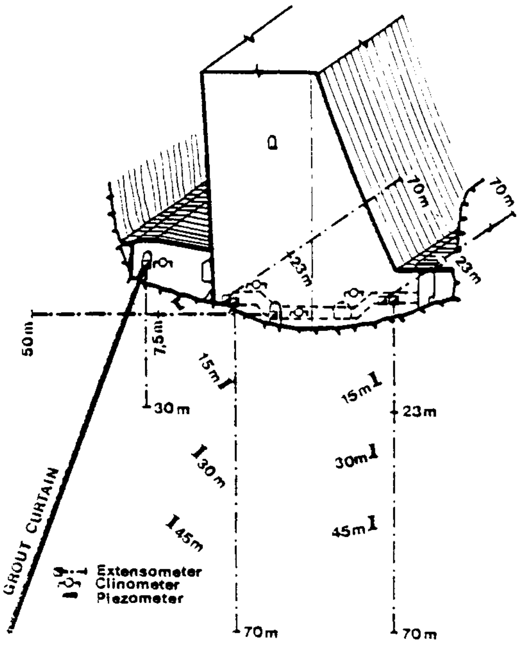
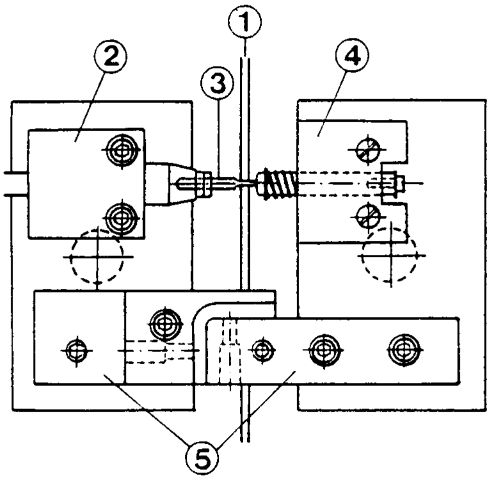


Fig. 5: Three-dimensional joint-meter



1 block joint

2 micro switch

3 adjustable part

4 elastic counterpart

5 three-dimensional local observation point (including metering clockwork)

Fig. 7: Measuring system of Moell arch dam

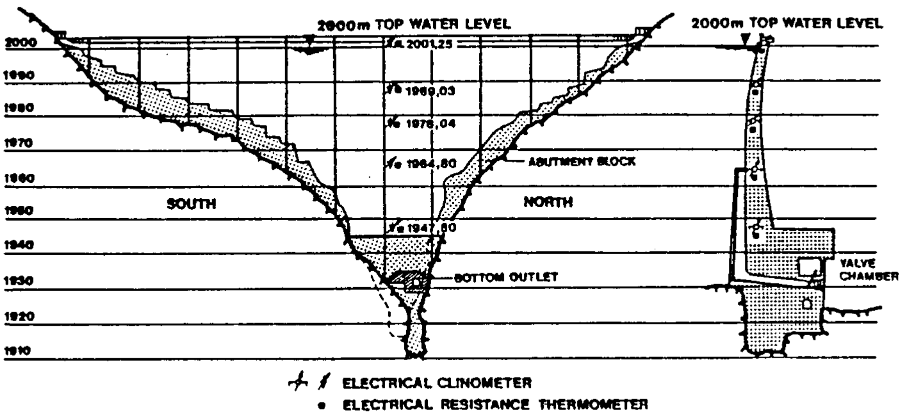
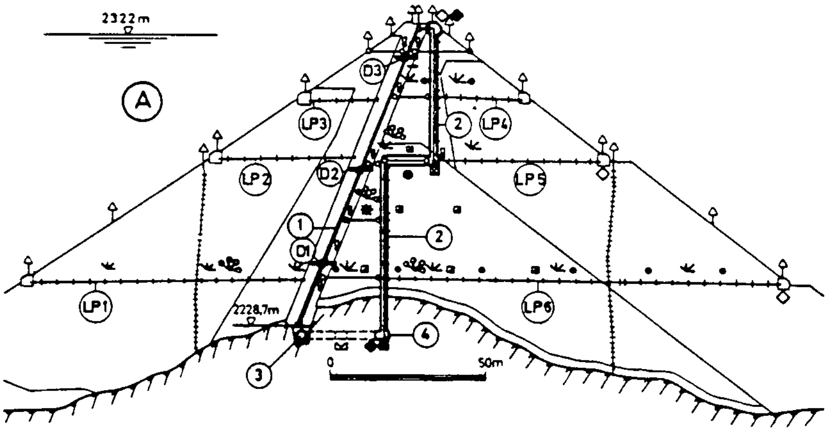


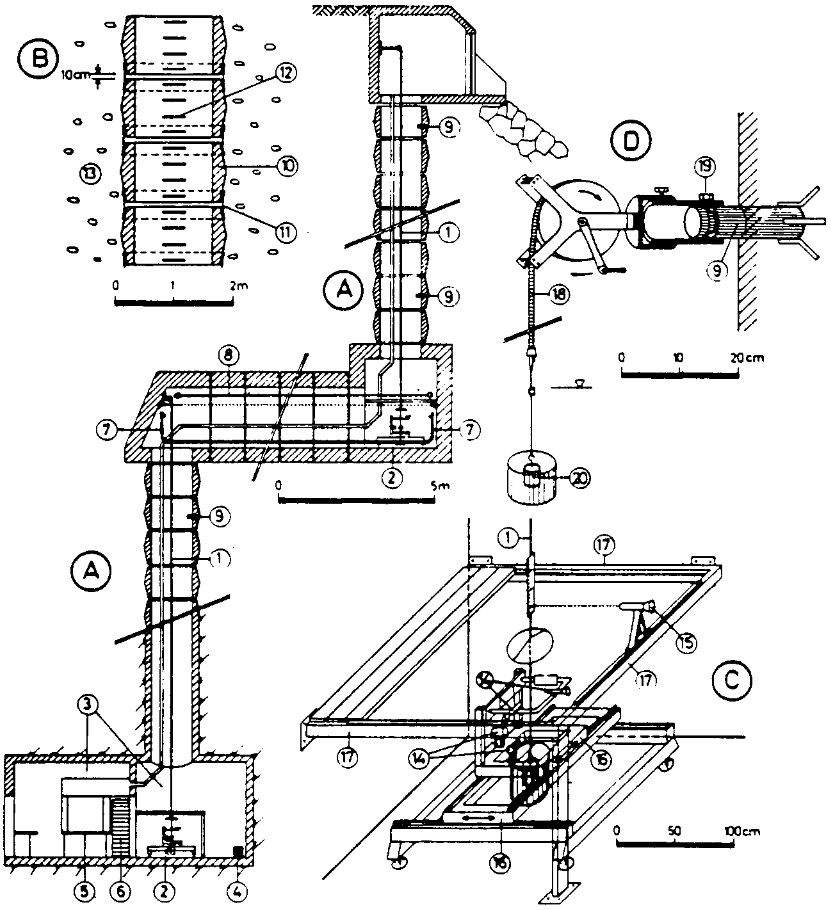
Fig. 8: Monitoring equipment of Finstertal dam



SYMBOL	MONITORING EQUIPMENT	NUMBER
1	Asphaltic concrete core wall	
2	Accessible pumb-line shaft 46m+56m	
3	Inspection and grouting gallery	
4	Central measuring chamber	
	measuring devices for the determination of core wall thickness variations	3
	horizontal plate gauges	6 + 2

SYMBOL	MONITORING EQUIPMENT	NUMBER
↑	surface monuments	111
‡	vertical plate gauges	7
○—○	extensometers	38
⚲	groups of 4 strain meters	4 x 4
▮	fluid level settlement devices	7
ǃ	plumb-lines	2
┘ └ ⋌ ⩛	two-dimensional group of earth pressure cells	83
✳	three dimensional group of earth pressure cells	18
▣	pore pressure cells	14
●	resistance thermometers	9
◆	strong motion accelerographs	2
◇	peak recording accelerographs	3
▲	piezometer tube in borehole	13
✉	recording of seepage water losses	3

Fig. 9: Details of shaft and plumb-lines



Ⓐ PLUMB-LINE SHAFT

① PLUMB-LINE 1,2 mm ② TELEMETRING DEVICE FOR PLUMB-LINE ③ CENTRAL MEASURING CHAMBER
④ STRONG MOTION ACCELLEROGRAPH ⑤ MEASURING DESK ⑥ AUTOMATIC MEASUREMENT OF EARTH AND POREPRESSURES
⑦ PERMANENTLY INSTALLED FLUID LEVEL ⑧ WIRE EXTENSOMETER ⑨ MEASURING PIN

Ⓑ SHAFT DETAILS

⑩ PREFABRICATED ANNULLAR ELEMENT ⑪ GEOTEXTIL (PERMEABLE PLASTIC FELT) WITH WIRE MESH
⑫ STIRRUPQ ⑬ BACKFILL OF MORAINE MATERIAL

Ⓒ PLUMB-LINE, DETAIL OF TELEMETRING DEVICE

⑭ DISPLACEMENT DEVICE (DIRECT READING AND TELEMETRING) ⑮ SETTLEMENT MEASURING
⑯ 2 FRAMES TO BE ADJUSTED WHEN PLUMBLINE DISPLACEMENTS EXCEED A MEASURING RANGE OF 100 mm
⑰ PLATEFORM FOR MEASURING WITH INTERMEDIATE PLUMB-LINE

Ⓓ INTERMEDIATE PLUMB-LINE WITH PORTABLE REEL

⑱ PLUMB-LINE WITH MEASURING TAPE ⑲ FIXING ⑳ PLUMB-BOB IN TANK WITH DAMPING OIL

Appendix C
Annexe C

REPORT BY THE CANADIAN NATIONAL COMMITTEE

1.0 INTRODUCTION

As part of the development of Canada many large dams have been constructed for hydroelectric power, domestic water supply, irrigation, flood control and navigation.

Because such dams store large volumes of water, it is essential that they be constructed to be safe, using the most up-to-date design criteria. As part of the design, each dam should be adequately instrumented so that its performance can be checked during construction, reservoir filling, and for the long term assessment of the structure.

This document provides instrumentation concepts and installations related to large dams constructed and to be constructed in Canada.

2.0 OBJECTIVES OF DAM INSTRUMENTATION

The main objectives of dam instrumentation/monitoring systems are:

1. To obtain data during construction of the dam and during first filling. Such data should signal any unusual or unexpected trends during construction or filling of the reservoir.
2. To provide data to assess the dam's performance during the years of operation.
3. To provide information on developing anomalies in the dam and to formulate appropriate remedial measures.

4. To provide data regarding design parameters used and to advance the knowledge of dam design.

3.0 SCOPE OF INSTRUMENTATION/MONITORING

The extent and scope of instrumentation to be installed in a dam should be determined early in the design. Some dams will require more extensive instrumentation systems than others. Factors that affect the types and amount of instrumentation are:

1. the "hazard rating" of the dam
2. type of dam
3. the height of dam and materials for construction
4. foundation conditions

The "hazard rating" assesses the seriousness of a dam failure on downstream populations and development. It should be noted that instrumentation in itself does not make a dam any safer. The dam must be designed and constructed using established criteria and incorporate safe measures within the design. Instrumentation will provide information on how the dam is performing as a water barrier and with this information remedial measures, if required, can be adopted in a timely manner to avoid any serious damage.

The type of dam and the internal zoning will define the types of instruments and the instrumentation system. Many types of instruments are available for embankment type dams and for concrete dams. Some devices will be discussed herein but the designer needs to review the various types of instruments available and select the best ones for the type of dam being designed.

The higher the dam the more water pressure being placed on the dam and the more load being applied to the foundation. All of the critical areas of the dam and foundation should be monitored with appropriate instrumentation. Instrumentation should be placed in planes for an embankment type dam. The planes should be located at critical zones of the dam and be either transverse or parallel to the dam axis, depending on measurements desired.

Foundation areas should be monitored for uplift pressures and hydrostatic pressures in rock or overburden material as well as for seepage flows and for deformation.

4.0 MONITORING SYSTEMS

4.1 Concrete Dams

A. General

i) Install a concentration of meters to provide sufficient data for analysis rather than having instruments scattered over a large area.

ii) Minimize the number of terminal stations by routing as many instruments as possible to each station.

iii) Provide convenient access to terminal stations.

iv) Minimize the number of different instrument types to reduce the variety of readout equipment.

v) Purchase and install electrical equipment to facilitate change over in the future to automated or remote data collection systems.

vi) Use a computer to store readings in chronological order, make required data corrections, compute results and plot results in a simple and meaningful manner.

vii) Instrumentation devices are subject to some abuse and damage during installation and concrete placement; therefore sturdy and reliable systems should be specified.

B. Deformation Measurements

Deformation of concrete dams can be measured by various devices. Some or all of these systems should be used on every concrete dam. Systems being used include:

i) Surface survey points located on the dam crest and along the downstream face to monitor both horizontal and vertical movement. The accuracy of the survey depends on equipment, methods and security of monuments.

ii) Plumblines located in wells or shafts to monitor tilting of the concrete dam. Vessels and floats are available for installation of inverted plumblines. For this arrangement the line is secured at the base of a dam and line tension is preferred because the measured offset is equal to movement of the dam.

iii) Rod extensometers extending from the base of the dam into the rock to monitor foundation displacements.

iv) Inclinometer casings drilled into bedrock and grouted into the dam concrete to monitor foundation movements.

v) Tiltmeters located in the concrete mass to measure tilt movement. A series of electric tiltmeters could be used to replace a manually read plumbline.

vi) Joint meters embedded in the concrete to monitor opening or closing of contraction joints and cracks.

C. Thermometers and Stress/Strain Measurements

Thermometers should be embedded to measure mass concrete temperature changes. A grid of thermometers is required to obtain mass concrete isotherms.

Construction thermometers are located throughout the dam to monitor temperatures during construction. They are not connected to the terminal stations and are abandoned as construction proceeds.

Stress and strain meters need not be used in concrete dams with heights below 45 m and anticipated stresses below 700 kPa. A minimum of three stress meters are required to calculate principal stresses (vertical, horizontal and 45°).

Strain meters should be used in areas that may be in tension.

D. Piezometric Pressures and Water Flow Measurements

Each concrete dam should have the following systems:

1. Devices to measure piezometric pressures in shear zones in the foundation rock, at the concrete/rock interface and adjacent to penstocks.

2. Electronic open-trench-type flumes to monitor flows in the dam galleries from foundation drains and leaks in the dam.

4.2 Embankment Dams

i) Pore pressure measurements should be measured in critical areas of the fill dam and in the foundation. The appropriate type of piezometer should be used to suit the location and material in which the piezometric level is being measured. There are many types of devices for measuring piezometric/pore pressure.

ii) Seepage flow should be accurately measured at locations where seepage occurs. In some cases it is best to isolate dam seepage into various areas of the dam by constructing isolation dykes within the dam embankment. Seepage flows are usually measured by V-notch weirs or a type of measuring flume.

iii) Deformation measurements are made in a fill dam by installing vertical measurement gauges and surface monuments. Vertical movement gauges are usually anchored to bedrock and rise as the fill is raised. They involve some disruption to fill placement and require care at time of installation. Special attention should be taken during the placing of fill in the instrument protection island to avoid differential movement between island and the dam mass. Vertical gauges provide a good measure of internal consolidation of the fill material as load is applied. Near vertical (sloping) gauges should be used with great care since raw data requires special treatment and results may be misleading if correction is not properly made. A more recent trend is to not install inclined gauges. The vertical movement gauges should be grooved so that a slope indicator device can be used to measure horizontal movement transverse and parallel to the axis.

Hydraulic settlement devices are available for installation within the dam fill. They provide an alternative means for measuring internal consolidation of the fill or foundation.

iv) Horizontal deformation within the dam fill should be measured in the critical areas where the dam fill is subject to relatively large horizontal loadings. Horizontal movement of the dam fill can be measured by operating a latchcone inside a horizontal movement gauge casing installed perpendicular to the dam axis in the downstream shell. The horizontal movement could also be measured by an Aquaducer probe to provide a settlement profile of the dam.

v) Stresses within the dam fill should be measured at certain critical locations of the dam like steep abutments or narrow gorges and at earthfill-concrete interfaces. The earth pressure cells provide a direct indication of stress distribution at the contact zone and monitor stress changes which may be indicative of changes in material strength of internal strains. Earth pressure cells measure total stress including pore pressure. To obtain effective stress at any particular cell location, a piezometer should be installed near the cell. Measurements from such devices can indicate whether hydraulic fracturing of the fill is taking place or arching is taking place between internal zones.

vi) Horizontal strain measurements are made in a fill dam by installing horizontal strain gauges. Horizontal strain gauges are usually anchored at one end of the dam in the abutment rock or to concrete abuting structures. The horizontal strain gauges should be placed in areas of potential tensile cracking such as steep abutments and abrupt changes in elevation of foundation rock.

5.0 PHYSICAL QUANTITIES AND INSTRUMENTS

5.1 General

The amount and types of instruments required for embankment and concrete dams depends on the size of the dam and the complexity of the structure and its foundation. Remoteness and poor accessibility are also factors to be considered. A conservative approach should be adopted.

The following components should be measured at most dams:

a) Piezometric levels within embankment dams and in the foundation of embankment and concrete dams.

b) Seepage flows into drainage galleries or adits and downstream of the dam.

c) Deformation of soils, rockfill and concrete.

d) Stress and stain in soils, rockfill and concrete.

e) Temperature within concrete and soil mass.

f) Frost depth penetration.

g) Seismic activity, natural and induced.

h) Reservoir levels.

i) Minimum and maximum air temperatures.

j) Rainfall and snowfall.

The designer needs to assess where he should have instrumentation planes and the locations for the various instruments.

Calibration, installation, maintenance and repair of instruments should be performed by experienced engineers.

5.2 Piezometers and Pressure Cells

Measurement of pore pressures in dam fills and in foundations is important to assess seepage conditions within a dam and uplift pressures in the dam foundation.

There are many types of piezometers available that suit the various locations in a dam: hydraulic, pneumatic and electric.

In critical locations it is prudent to install two differing types so a backup measurement is available.

Pneumatic and/or electric type piezometers are used where the piezometer tip is remote from the readout area and where the piezometric level will remain relatively low.

Hydraulic (twin tube) type piezometers are used where pore pressures will be relatively high. They are usually connected to pressure gauges in the terminal house.

The number and location of each type of piezometer has to be determined by the designers to suit type and height of dam and foundation conditions. As piezometers malfunction and fail for various reasons it is prudent to install more than that needed to make a reasonable assessment of a dam's performance.

Instrumentation leads should not extend across the core of an embankment dam. When riser pipe is used to bring several piezometers up to the crest and soil island is used to protect the pipe, good quality control of fill placement should be exercised to avoid differential compaction and potential subsidence.

Pressure cells can be installed in a pocket of the rock surface at the concrete-rock contact for concrete dams. These measure the uplift pressure against the concrete surface. Total pressure cells in embankment dams are difficult to properly install and require great care.

5.3 Seepage Flows

Seepage devices should be installed to collect and measure all seepage that enters drainage galleries or abutment drainage adits and areas downstream of the dam.

Seepage measuring devices are usually V-notch weirs or measuring flumes. Measuring flumes can be adapted to provide automatic recording of seepage flows.

Accurate and continuous measurement of changes in seepage along with frequent and vigilant visual inspection will provide a very positive and quick means to assess any developing problems at a dam.

The designers should locate weirs or flumes in critical areas to ensure all seepage is collected and conducted to the measuring device.

5.4 Deformation Measurements

Devices for measuring deformation are required to measure the embankment fill performance during construction and over the longer term operation of the reservoir.

Various devices are available for measuring deformation or consolidation of dam fill during construction and after the dam is completed. Some of these are:

> Cross arm devices, magnetic probe, slope indicators, extensometers, hydrostatic settlement devices, and surface survey settlement points.

Such devices should be placed in strategic locations in the dam fill. Deformation measurements should be made in the area of highest fill (lowest foundation level) and in areas of abrupt changes in the foundation.

Deformation measurements of concrete dams are made by installing surface survey points, pendulums/plummets, inverted pendulum, optical plummets, and inclinometers/tiltmeters. Also, extensometers are used to measure concrete dam movement with respect to the foundation.

5.5 Stress and Strain Measurements

Strain gauges are placed in fill dams near steep abutments and across areas of abrupt changes in the foundation. Such gauges are also placed where the earthfill connects to concrete transitions or walls.

These devices measure internal soil strains in the areas of potential differential movement and should give an indication of any cracking developing.

Devices used to measure strain in fill dams are Resistance Type Gauges and Carlson Strain Meters. Also, Vibrating Wire Strain Gauges and Resistance Type Gauges have been used in concrete dams.

Stress measurements are made in concrete dams by using joint meters to monitor joint-crack openings.

5.6 Temperature Measurement

The measurement of the internal temperature of mass concrete during construction of a concrete dam is important and should be carried out by installing many temperature indicating devices throughout the concrete mass. The temperature rise and cooling have to be carefully controlled to avoid cracks in the mass concrete. In embankment dams, temperature measurement is often necessary in order to apply proper correction to sealed piezometers and pressure cell readings.

5.7 Seismic Activity

Devices to measure seismic activity should be installed in all large dams. If seismic activity is recorded at the site the dam should be thoroughly inspected for any damage. Efforts should be made to measure natural site activity prior to construction, in order to distinguish natural activity from induced seismic activity. Construction blasting should also be recorded to assess natural and induced seismicity.

5.8 Reservoir Level

The reservoir level should be recorded at the time of making any instrumentation readings. Usually an automatic recording system is used to document reservoir levels and such information is readily available to the instrumentation observer.

5.9 Ambient Temperatures

The daily minimum and maximum temperatures at the dam site should be recorded.

5.10 Climatic Conditions

Severe climatic conditions at a dam site should be recorded. Intense rainfall or snowmelt could affect instrumentation readings and the observer should be cognizant that changes in observations are due to climatic conditions and not initiated by the pressure of stored water.

5.11 Frost Depth Penetration

In northern regions, frost can penetrate embankment dams down to several metres and affect the top part of the impervious core, generally made of frost susceptible material. Frost depth should be measured using Grandahl penetration indicators, thermistors or thermo-couples. Frost heave could also be monitored.

6.0 OBSERVATION FREQUENCIES

The frequency for reading the various instrumentation devices varies with stage of construction/operation and with the performance of the dam.

During construction of the dam all devices are read at least once-a-week and whenever the tubes or leads are extended to suit raising of the dam.

At the end of construction and prior to starting to fill the reservoir a datum set of readings of all devices should be carefully made as this will be the base for comparing all subsequent readings during reservoir filling and for long term operation.

Observations made during filling should be quite frequent: piezometers and seepage weirs once-a-day, others once-a-week and surface surveys once-a-month. This frequency should be maintained until reservoir has reached full pool and for a few months after. The frequency of readings at Revelstoke dam are shown on Fig. 1 and the frequency developed for the La Grande Complex is given on Fig. 2. Once the general patterns of readings have been established the frequency of readings may be lengthened to suit the design engineers' requirements.

A detailed surveillance program should be developed prior to reservoir filling and knowledgeable people assigned to various duties to ensure that surveillance of the dam and reservoir slopes are properly carried out. Also, a long term surveillance program should be developed for use by the observers. Design engineers should be involved in an annual inspection of the dam and preparing an annual report for the owner.

7.0 AUTOMATIZATION OF MEASURING SYSTEM

With the advent of small computers, key devices at a dam can be automated to provide recorded readings at central locations, such as the local powerhouse or engineer's office in the city. With automated devices the frequency of on-site readings could be reduced.

Also, if observational data is computerized the necessary charts can be printed by a printout device connected to the computer system.

In some areas it may be necessary to install early warning devices or alarms and these can be done with certain automatic devices sending signals directly to the powerhouse or engineer's office on the owner's microwave system.

As automated devices are subject to sending false alarms more than one alarm system should be installed. Emergency action should not be put into effect unless the multi-alarm system is signalling a problem.

An automatic system still requires maintenance and visual inspection of the dam. It is important that any alarm should be checked out immediately. Whether or not a partially automated system exists, periodic visual inspections are still required of the dam and adjacent areas.

8.0 ANALYSIS OF OBSERVATION DATA

Based on design parameters, expected threshold levels should be established for certain key devices. The operating staff should be advised of such levels.

During filling of the reservoir all data should be analysed as soon as it is available to assess the dam's performance as the load is gradually increased and periodic reports perpared by or for the design engineer.

The site observers should be trained to take accurate observations and not to "cover-up" any readings that appear to be inconsistent with previous readings. Recorded data should be documented and passed to the engineering office for assessment.

A detailed annual inspection should be made of the dam and reservoir shoreline and an annual report prepared as to the performance of the dam over the past year.

9.0 EXISTING DAMS

Existing dams should undergo a comprehensive inspection and review every 5 or 6 years.

Some old dams do not have adequate instrumentation to check the dams condition after many years of operation. The engineer should critically assess such dams and recommend the installation of devices to check the adequacy of the dam over the remaining life of the plant.

As dams become old they tend to deteriorate and some nominal instrumentation will help establish the desired remedial measures to keep the dam in an acceptable operating condition.

STAGE		INSTRUMENTS									
		Core Piezometer	Foundation and Shell Piezometer	Vertical Movement Gauge	Horizontal Movement Gauge	Horizontal Strain Gauge	Surface Monument	Earth Pressure Cell	Weir and Well	Strong Motion Accelerograph	Visual Inspection
DURING CONSTRUCTION		FREQUENTLY BY FIELD STAFF				1/month	1/month	1/month	1/month	Continuous	1/month
RESERVOIR FILLING		1/2 days	1/2 days	1/week	2/month	2/month	1/month	2/month	1/2 days	Continuous	1/day
AFTER THE FIRST RESERVOIR FILLING	First 6 month	1/week	1/week	1/month	1/month	1/month	1/month	1/month	1/week	Continuous	1/day
	6 Month to 1½ Year	2/month	2/month	4/year	4/year	4/year	4/year	4/year	2/month	Continuous	1/week
	1½ Year to 2½ Year	2/month	2/month	4/year	4/year	4/year	4/year	4/year	2/month	Continuous	1/week
	2½ Year to 6½ Year	6/year	6/year	2/year	2/year	2/year	2/year	2/year	6/year	Continuous	2/month
	Subsequent Years	2/year	2/year	1/year	1/year	1/year	1/year	1/year	2/year	Continuous	1/month

REVELSTOKE PROJECT
EARTHFILL DAM MONITORING

FIG.1

STAGE		INSTRUMENTS						
		SEALED PIEZOMETER	CASAGRANDE TYPE PIEZOMETER	INCLINO-METER	FROST	SURFACE MONUMENT	EXT., TPC, SC (*)	WEIR
DURING CONSTRUCTION	CONSTRUCTION PERIOD	1/month	1/month	6/year	-	-	1/month	-
	INTERIM PERIOD	1/season	1/season	1/season	-	-	1/season	-
RESERVOIR FILLING		1/2 days	1/day	2/month	1/month	2/month	2/month	2/week
AFTER THE FIRST RESERVOIR FILLING	FIRST YEAR	1/week	1/week	6/year	1/month	1/month	1/season	2/week
	SECOND YEAR	2/month	2/month	1/season	1/month	1/seasor	1/season	1/week
	3rd to 5th YEAR	6/year	1/month	2/year	1/month	2/year	2/year	1/month
	SUBSEQUENT YEARS	2/year	4/year	1/year	1/month	1/year	1/year	6/year

* EXT: Extensometer
TPC: Total Pressure Cell
SC : Settlement Cell

LA GRANDE COMPLEX

FREQUENCY OF INSTRUMENT READINGS

FREQUENCE DE LECTURE DES INSTRUMENTS

FIG. 2

LA GRANDE COMPLEX

Re: Q52, R4, ICOLD R10, 1982

Appendix D
Annexe D

RAPPORT PAR LE COMITÉ NATIONAL FRANÇAIS

REPORT BY THE FRENCH NATIONAL COMMITTEE

Résumé

Le rapport comprend les chapitres suivants :

1 - Législation française en matière d'inspection et de surveillance des barrages

2 - Organisation de l'auscultation des barrages à Electricité de France

3 - Quelques principes servant de bases à l'auscultation des barrages

4 - Paramètres significatifs du comportement des barrages et choix des appareils de mesures . Evolution de la conception des dispositifs d'auscultation au cours de ces dernières années

5 - Automatisation des mesures d'auscultation

6 - Cas des barrages anciens

7 - Analyse et interprétation des résultats des mesures d'auscultation au cours de la construction, de la première mise en eau et de l'exploitation normale des barrages.

Summary

The report contains the following chapters :

1 - French legislation on inspection and surveillance of dams

2 - Organization of monitoring in Electricité de France

3 - Some principles of dam monitoring

4 - Significant parameters and choice of instruments. Recent developments in monitoring design

5 - Automation of instrument readings

6 - Old dams

7 - Analysis and interpretation of measurements during construction, first filling and normal operation.

Rapport préparé par Y. LE MAY, Ancien Secrétaire Général du Comité Français des Grands Barrages.

Report prepared by Y. LE MAY, Past Secretary General of the French Committee on Large Dams.

INTRODUCTION

L'auscultation d'un barrage comprend l'ensemble des opérations ayant pour objet la mesure, avec le maximum de précision, de divers paramètres susceptibles de caractériser, à l'instant considéré, l'état de l'ouvrage.

L'analyse et l'interprétation des résultats des mesures doivent aboutir à une connaissance, aussi complète que possible, du comportement de l'ouvrage pris dans son ensemble -barrage et fondation- ou dans ses parties.

L'auscultation répond essentiellement à deux objectifs :

- d'une part, le contrôle de la sécurité du barrage, vis-à-vis de la détérioration et de la rupture, de façon que puissent être entreprises suffisamment tôt les opérations nécessaires à l'entretien de l'ouvrage et à sa sécurité,

- d'autre part, l'analyse du comportement du barrage, afin de tirer des enseignements pour la conception et le calcul des ouvrages futurs.

Le présent rapport s'appuie essentiellement sur l'expérience acquise, dans le domaine de l'auscultation, par ELECTRICITE DE FRANCE qui exploite à ce jour quelque 150 barrages (sur les 450 barrages de plus de 15 m de hauteur au-dessus de la plus basse fondation, en service en FRANCE).

Avant la nationalisation de l'électricité en 1946, les Sociétés de production d'énergie électrique avaient certes mis en place, sur les quelques grands barrages qu'elles exploitaient, des dispositifs d'auscultation destinés au contrôle du comportement de ces ouvrages.

Mais ces dispositifs étaient disparates d'un ouvrage à l'autre. Dans bien des cas, les opérations de mesures et leur dépouillement étaient longs. De plus, très souvent, l'interprétation des mesures ne pouvait pas être effectuée rapidement du fait de l'absence de méthode rationnelle d'analyse.

La nationalisation de l'électricité a permis de repenser le problème de l'auscultation et d'étudier, sur le plan national, les moyens à mettre en oeuvre pour assurer un contrôle efficace et homogène des barrages.

1. LA LEGISLATION FRANCAISE EN MATIERE DE SURVEILLANCE DES GRANDS BARRAGES

La législation française impose, pour les barrages intéressant la sécurité publique, une inspection et une surveillance.

Les instructions ont été définies dans une circulaire interministérielle du 14 Août 1970, mettant à jour les précédentes circulaires de 1927 et de 1928.

Cette circulaire de 1970 s'applique à tous les barrages d'une hauteur au moins égale à 20 mètres au-dessus du terrain naturel et, également, à ceux de moindre hauteur, dont la rupture aurait des conséquences graves pour les personnes.

La surveillance d'un barrage incombe au propriétaire de l'ouvrage.

Le Service de l'Etat, chargé du Contrôle, doit s'assurer que cette surveillance est convenablement remplie par le propriétaire.

INTRODUCTION

Monitoring a dam consists of all the operations of measuring as accurately as possible the parameters which describe at any moment in time the condition of the structure.

Analysis and interpretation must provide as complete a knowledge as possible of the behaviour of both dam and foundation.

Two objectives must be met :

- checking the safety so that appropriate timely maintenance can be undertaken to prevent deterioration and failure,

- gathering data for the design of future structures.

This French report relates mainly the experience in dam monitoring, of Electricité de France (EDF) which currently operates 150 dams (out of a total of 450 more than 15 m high in France).

Before nationalization of electricity in 1946, the power companies had, of course, installed instruments in some of their large dams. There was, however, no coordination and measurement and processing took a lot of time. Data interpretation could not be done quickly in many cases, because there was no rational method of analysis available.

Nationalization allowed the whole subject of instrumentation to be rethought on a national level and an effective and homogeneous system to be developed.

1. FRENCH LEGISLATION ON INSPECTION AND SURVEILLANCE OF DAMS

French law requires inspection and surveillance of dams that might affect public safety.

The instructions are set out in an "interministry circular" dated 14 August 1970 bringing up to date earlier circulars of 1927 and 1928.

The circular applies to all dams more than 20 m high (above natural ground level) and to all others whose failure would have serious consequences for human life.

The surveillance of a dam is the responsibility of its owner.

A special Government Department ensures that this surveillance is properly carried out by the owner.

Les principales instructions contenues dans la circulaire précitée sont les suivantes :

- Dossier du propriétaire

Le propriétaire devra constituer ou tenir à jour un dossier contenant tous les documents relatifs aux ouvrages : plans d'exécution, résultats des reconnaissances géologiques et géotechniques, renseignements hydrologiques, description des travaux d'entretien et de réparation, plans des dispositifs d'auscultation, résultats des mesures, documents relatifs à l'exploitation de la retenue, etc...

- Première mise en eau

Les dispositions prévues pour la surveillance du barrage pendant la première mise en eau doivent être soumises à l'approbation de l'Administration (1), en même temps que le projet de l'ouvrage. Les mesures devront commencer en général dès le début de la construction.

Ces dispositions devront comprendre :

- la description et les plans de situation des appareils d'auscultation,

- le programme de remplissage de la retenue, prévoyant,en particulier, des paliers pour l'exécution des mesures,

- la fréquence des mesures,

- les consignes en cas d'anomalies sur le barrage (manoeuvre d'urgence des organes d'évacuation - Services et Autorités à prévenir immédiatement)

Le propriétaire devra remettre au Service du Contrôle, dans les six mois de l'achèvement de la première mise en eau, un rapport contenant une analyse détaillée du comportement de l'ouvrage au cours de cette opération.

Les conclusions de ce rapport devront être complétées dans le rapport que l'exploitant de l'ouvrage devra remettre, par la suite, chaque année à l'Administration.

- Registre de l'exploitant

L'exploitant du barrage doit tenir, dès le début de la première mise en eau, un registre sur lequel seront mentionnés, au fur et à mesure, les principaux renseignements relatifs à l'exploitation du réservoir (remplissage, vidange, crue, manoeuvre des vannes), les incidents constatés sur l'ouvrage (fuites, fissures,...), les travaux d'entretien ou de réparation,...

- Surveillance des ouvrages en exploitation normale

La surveillance des barrages par l'exploitant comporte essentiellement

- d'une part, les visites périodiques, qui ont pour but l'examen visuel de l'ouvrage, de ses abords, de ses organes d'évacuation,

- d'autre part, les mesures sur les appareils d'auscultation.

Les périodicités des visites et des mesures peuvent varier selon l'importance de l'ouvrage et selon les constatations faites, leur fréquence étant augmentée notamment si une anomalie est constatée.

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(1) Comité Technique Permanent des Barrages, qui est un Comité interministériel créé en 1966.

The principal instructions in the circular are :

- Owner records

The owner must create or keep up to date records containing all documents relating to the structure, including construction drawings, results of geological and geotechnical investigations, hydrological data, description of maintenance and repair works, drawings of the instruments, results of measurements, documents relating to reservoir operation, etc.

- First filling

Proposals for procedures during first filling must be approved by the "Comité Technique Permanent des Barrages" (Permanent Technical Committee on Dams), an interministerial committee created in 1966. The proposals must be submitted at the same time as the design of the project.

The proposals have to include :

- description and layout of instruments,

- filling programmme including pauses for measurements,

- reading frequency,

- steps to be taken in case of problems (emergency drawdown, who is to be informed).

The owner must report fully to the Government Department within 6 months after filling, and the report must contain a complete analysis of the behaviour of the dam during the first filling.

It is amplified as necessary in an operator's annual report.

- Operator's register

The operator must maintain a register containing the principal operating data such as filling, emptying, floods, gate operation, leakages, fissures, maintenance, repairs etc.

- Normal operating surveillance

This basically consists of :

- periodic inspections of the structure, surrounding area and discharge equipment,

- instrument readings.

The frequency of inspections depends on the size of the dam and the occurrence of problems.

L'exploitant devra adresser chaque année au Service du Contrôle un rapport sur la surveillance et l'auscultation du barrage donnant, d'une part, des renseignements sur l'exploitation de l'ouvrage au cours de l'année, sur les incidents constatés et les travaux effectués, et, d'autre part, les résultats des mesures d'auscultation et leur interprétation. Ce rapport comportera obligatoirement, tous les deux ans, une analyse approfondie de l'évolution du comportement de l'ouvrage.

- Visites du Service du Contrôle

Le Service du Contrôle procédera chaque année, pour chaque barrage, à au moins une visite, en présence de l'exploitant. Cette visite comportera l'examen visuel des parties non noyées, le contrôle du bon état de fonctionnement des ouvrages d'évacuation, de vidange, des drains, des dispositifs d'auscultation...

Le Service du Contrôle procédera, moins de cinq ans après la mise en service du barrage, à une visite complète comprenant, entre autres, l'examen des parties habituellement noyées des ouvrages. Les visites complètes ultérieures auront lieu tous les dix ans.

Ces visites nécessiteront en principe une vidange complète de la retenue. Toutefois, si une telle vidange soulève des difficultés spéciales, la visite complète des parties noyées pourra être effectuée au moyen d'un petit sous-marin, d'une caméra de télévision étanche.

- Révision spéciale des barrages anciens

Les règles de l'art ont évolué depuis la construction de nombreux barrages anciens. Bon nombre de ces ouvrages comportent des dispositifs d'auscultation très réduits (voire inexistants), non comparables avec les dispositifs mis en place actuellement sur les barrages de même type, ceci bien que ces barrages anciens présentent parfois des facteurs de sécurité moindres que ceux actuellement admis.

Pour ces ouvrages anciens, la circulaire du 14 Août 1970 a prévu une révision spéciale. Chaque Service du Contrôle est chargé d'établir une liste des barrages lui paraissant devoir faire l'objet d'une révision, en indiquant un ordre d'urgence pour la révision et en donnant les motifs.

Après consultation du Comité Technique Permanent des Barrages, le Service du Contrôle invitera le propriétaire à faire procéder par des Ingénieurs ou un Bureau d'Etudes qualifiés à une inspection spéciale de l'ouvrage se traduisant par l'établissement d'un rapport.

Ce rapport doit notamment proposer les appareils d'auscultation à installer en vue d'améliorer la sécurité de l'ouvrage et d'en rendre la surveillance plus précise et plus efficace. Il est soumis au Comité Technique Permanent des Barrages.

The operator's annual report must be sent to the Government Department, giving the information in the operator's register and the results of measurements. Every two years, this report must contain a full analysis of the dam's behaviour.

- Visits by the Government Department

The Government Department makes at least one visual inspection of each dam annually with the operator.

Within 5 years after first filling, the Government Department makes a full inspection of each dam. This includes inspection of parts normally submerged. Thereafter, this inspection is repeated every ten years.

In principle, such inspections require the reservoir to be emptied. However, if this would cause serious problems, miniature submarines or underwater TV can be used.

- Special rules for old dams

Old dams were not built on modern design criteria. Many have little or no instrumentation, even though safety factors are lower than would be accepted nowadays.

The circular of 14.08.70 provides for a special review of these dams. Each Government Department has to list the dams thought to need such review and give an order of priority. The owner is then invited to commission a report by engineers or consultants, containing inter alia recommendations on the instruments to be installed. The report is submitted to the Permanent Technical Committee on Dams.

2. ORGANISATION DE L'AUSCULTATION DES BARRAGES A ELECTRICITE DE FRANCE (EDF)

Comme exemple d'organisation des mesures d'auscultation, nous indiquerons celle mise en place par ELECTRICITE DE FRANCE.

2.1. Le Comité d'Auscultation d'EDF

A ELECTRICITE DE FRANCE, trois Directions sont concernées par les problèmes d'auscultation :

- La Direction de l'Equipement, chargée de l'étude et de la construction des aménagements de production d'énergie électrique.

La responsabilité de l'auscultation d'un barrage, du point de vue de la sécurité, pendant sa construction et sa première mise en eau, incombe à cette Direction. A ce premier objectif s'ajoute le souhait de retirer des mesures des enseignements en vue de la conception et du calcul des ouvrages futurs.

- La Direction de la Production et du Transport (Service de la Production Hydraulique) qui, après mise en service des ouvrages, prend en charge leur exploitation et, entre autres, leur auscultation.

- La Direction des Etudes et Recherches qui, conduisant des études, des calculs et des essais sur les structures et les matériaux, souhaite en confronter les résultats avec les éléments fournis par l'auscultation des ouvrages.

Ces trois Directions ont estimé, d'un commun accord, qu'il était nécessaire d'assurer une liaison entre elles dans le domaine de l'auscultation. Aussi décidèrent-elles, en 1949, de créer un "Comité d'Auscultation" (1) qui regroupe des représentants de ces trois Directions, lesquels peuvent solliciter des concours, permanents ou non, de spécialistes extérieurs à EDF

Le rôle du Comité est d'assurer entre les trois Directions une coordination et une harmonie de points de vue, tant en ce qui concerne la doctrine que la pratique des mesures, ainsi qu'une information réciproque sur les travaux exécutés ou prévus.

2.2. Les travaux d'auscultation au sein de chaque Direction

2.2.1. Direction de l'Equipement

La Région d'Equipement (2) concernée établit le projet d'auscultation qui est soumis à l'avis du Comité d'Auscultation.

La Région d'Equipement est également responsable :

- de la mise en place des appareils,

- de l'exécution des mesures,

- du traitement des informations recueillies et de l'établissement des états correspondants,

- de l'interprétation des mesures.

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(1) Les activités du Comité qui, au début, se limitaient aux barrages ont été étendues, en 1966, aux grands ouvrages thermiques et nucléaires.

(2) Actuellement, deux Régions sur les cinq existantes sont chargées des travaux d'équipement hydraulique à EDF

2. ORGANIZATION OF MONITORING IN EDF

The EDF organization on dam monitoring matters is described, as an illustration of the way this issue may be approached.

2.1 Monitoring Committee

At EDF 3 Divisions are concerned in dam monotoring :

- Construction Division, which undertakes the design and construction of dams and power plants.

This Division has responsibility for dam safety during construction and first filling. Information useful for the design of future projects is also obtained.

- Generation and Transmission Division, which, after commissioning, is charged with the operation and monitoring of EDF dams.

- Research and Development Division, whose responsibility is to conduct studies and tests on materials and structures, keeps itself informed of the results of monitoring.

These three Divisions having agreed that close liaison was needed, they formed a Monitoring Committee in 1949, on which each is represented (1). Non-EDF specialists may be called in. The role of the committee is to coordinate monitoring policy and practice between the three Divisions, and to disseminate information on existing and proposed installations.

2.2 Work done within each Division

2.2.1 Construction Division

The relevant Construction Region (2) submits proposed instrumentation system arrangements to the Monitoring Committee.

The Region is also responsible for :

- intrument installation,
- measurements,
- data processing,
- interpretation.

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(1) Originally confined to dams, subsequently extended to include major fossil-fuelled and nuclear powerstations.

(2) Two of the five EDF Construction Regions are concerned with hydro power development today.

La Région peut recevoir, aux divers stades de ces travaux, l'assistance technique des Services spécialisés d'EDF et, éventuellement, d'Entreprises et d'Ingénieurs Conseils.

C'est ainsi qu'en particulier une collaboration s'est créée entre la Direction de l'Equipement et la Direction de la Production et du Transport dès l'élaboration du projet d'auscultation et dès le début de la mise en place des appareils, la Division Technique Générale (DTG) du Service de la Production Hydraulique de cette dernière Direction intervenant comme conseil à ces deux stades. De plus, le personnel d'exploitation, dont une partie s'installe sur l'aménagement bien avant l'achèvement des travaux, et la DTG participent aux premières mesures d'auscultation.

Cette collaboration entre les deux Directions ainsi que l'établissement par les Services de l'Equipement, avant le transfert du barrage au Service de la Production Hydraulique, d'un dossier d'auscultation très complet facilitent ce transfert.

Ce dossier d'auscultation comprend, entre autres, les résultats des mesures, leur interprétation, l'ensemble des données, observations faites en cours de travaux et de mise en eau, permettant de porter un jugement sur le comportement de l'ouvrage.

La règle habituelle est que le transfert du barrage se fait après un *remplissage jusqu'à la cote normale de retenue, suivi d'une vidange*, sous la condition que le comportement de l'ouvrage ait été jugé satisfaisant. Dans le cas contraire, le transfert est différé.

2.2.2. Direction de la Production et du Transport

Le Service de la Production Hydraulique de la Direction de la Production et du Transport a la charge d'exploiter l'ensemble des installations hydroélectriques d'EDF, dont les barrages.

Ce Service comprend actuellement neuf Groupes Régionaux de Production Hydraulique. Le Chef de chaque GRPH est responsable de la sécurité des barrages situés sur son territoire.

La majorité des mesures d'auscultation sont effectuées par le personnel d'exploitation au cours des visites périodiques qui sont aussi l'occasion d'une observation visuelle du barrage et de ses abords.

Les résultats des mesures d'auscultation sont l'objet de plusieurs traitements:

- le premier stade est assuré, sur place, immédiatement après l'exécution des mesures avec des moyens simples, tels que la tenue à jour manuelle de graphiques de quelques-unes des grandeurs mesurées, en fonction du temps et de la cote du plan d'eau.

- le deuxième stade est assuré par un Centre Régional d'Auscultation (1), dépendant de la DTG, à qui les résultats sont transmis par la poste sur des imprimés spéciaux. Chaque Centre Régional d'Auscultation vient d'être équipé d'un terminal relié au Centre de calcul de la DTG situé à GRENOBLE. Ce terminal permet ainsi de transmettre au Centre de calcul les lectures, après un contrôle succinct de vraisemblance ; il reçoit également, en retour du Centre de Grenoble, les résultats du calcul des grandeurs interprétables, leur

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(1) Actuellement, existent quatre Centres d'Auscultation, disposant d'une quarantaine de personnes pour la surveillance de quelque 150 barrages.

It may be helped by other specialist groups within EDF and, if necessary, by outside contractors and consultants.

In this way, collaboration is established between the Construction Division and the Generation and Transmission Division from the beginning of both instrumentation design and its installation. The General Technical Branch (Division Technique Générale , DTG) of the Generation Division's Hydro Generation Department acts as adviser in both stages. Operating personnel, who arrive on site well before the works are complete, and DTG take part in the early measurements.

A very detailed monitoring report containing all available information is established by the Construction Division before transfer of the project to the Generation and Transmission Division.

Transfer is normally made after first filling to retention water level and a drawdown, provided the structure is thought to behave correctly. If not, transfer is delayed.

2.2.2 Generation and Transmission Division

The Hydro Generation Department of this Division has responsibility for the operation of all EDF hydro powerplants. It contains at present 9 Regional Groups, whose chief engineers are responsible for the safety of all dams in their areas.

Most measurements are made during periodic inspections by the operating staff, which include visual inspection.

The data are processed in various ways :

- in the first stage, simple means are used on site immediately after readings are made, such as manually plotting some of the parameters against time and reservoir level.

- the second stage is carried out by a Regional Monitoring Centre (1) which receives the readings through the post on special forms. Recently, each Regional Centre has been equipped with a mini-computer connected to the DTG computer centre in Grenoble, to which they send the monitoring measurements, after a rapid credibility check. In return, the Regional Centre receives the computations of interpretable quantities and conversion of the raw data to

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(1) The four Regional Centres, with a staff of about forty, cover some 150 dams in all.

transposition en grandeurs corrigées des effets hydrostatiques et thermiques à l'aide de "modèles de comportement" calés sur un échantillon de mesures antérieures, et leur restitution sous forme numérique ou graphique.

Cette phase de calcul centralisé est fortement automatisée et organisée pour réduire au minimum les interventions humaines.

Par contre, l'intervention humaine reprend toute son importance au niveau de l'interprétation des résultats des mesures corrigées.

Un travail de synthèse interprétative est effectué systématiquement par les Ingénieurs des Centres d'Auscultation tous les deux ans, pour chaque ouvrage, et fait l'objet d'un rapport d'auscultation.

Cette organisation qui ne fait place qu'exceptionnellement aux dispositifs automatiques locaux pour la collecte des données, jamais pour leur analyse, présente les avantages suivants :

- elle oblige à des visites rapprochées des ouvrages, considérées comme essentielles,

- elle évite la démobilisation des exploitants vis-à-vis de la sécurité,

- elle confie la délicate fonction d'interprétation fine des résultats des mesures à des ingénieurs qui, grâce au large éventail d'ouvrages dont ils ont la charge, ont acquis une solide expérience.

2.2.3. Direction des Etudes et Recherches

Cette Direction est consultée sur le projet d'auscultation. Elle peut utilement confronter les résultats des calculs susceptibles de lui être confiés avec les résultats d'auscultation de l'ouvrage réel.

3. QUELQUES PRINCIPES SERVANT DE BASES A L'AUSCULTATION DES BARRAGES

3.1 Les barrages sont des ouvrages à longue durée de vie ; il est donc nécessaire de disposer d'appareils de contrôle fiables sur des durées de vie équivalentes. Cela donne une particulière importance aux appareils accessibles, dont le bon fonctionnement est vérifiable, dont le remplacement est envisageable sans crainte de discontinuité dans les séries de mesures.

3.2 L'auscultation s'applique à des phénomènes de faible amplitude et vise à détecter suffisamment tôt des discontinuités, des évolutions significatives, traduisant des désordres. Elle doit donc mettre en oeuvre des instruments très sensibles.

3.3 Les appareils simples sont à rechercher ; des lectures rapides et fréquentes pourront être ainsi effectuées par le personnel du chantier ou de l'exploitation sur place, sans faire appel à des spécialistes, ce qui permettra un contrôle suivi du comportement de l'ouvrage et une exploitation statistique des résultats.

3.4 Une évolution fondamentale qui s'est manifestée au cours des dernières décennies est l'importance de plus en plus grande accordée à la surveillance des fondations dans le domaine des déformations et du fonctionnement hydraulique.

numerical and graphical form after correction for hydrostatic and temperature effects, using "behaviour models" calibrated from earlier measurements.

This centralised computation is highly automated to keep human intervention to a minimum. But human skills become paramount when it comes to actually interpreting the processed records.

The Monitoring Centre's engineers study and interpret all available data on a dam every two years and a full report is written.

This organization, which only in exceptional circumstances uses automatic devices at local level for data collection (but never for analysis), has the following advantages :

- it necessarily encourages frequent inspections (considered extremely important for safety),
- it prevents operating staff from evading their responsibilities regarding safety,
- it puts the delicate task of data interpretation in the hands of engineers with wide experience of a large number of dams.

2.2.3 Research and Development Division

This Division advises on instrumentation system design. It can usefully compare records from particular dams with the theoretical results from dams it has analysed.

3. SOME PRINCIPLES OF DAM MONITORING

3.1 Dams are structures with a long life span. Reliable instruments with a similar life span are necessary, and they must be accessible, verifiable and replaceable.

3.2 They must be sensitive to give early warning of sudden changes or trends that are very small but may be significant indicators of distress.

3.3 They should be simple so that frequent readings can be made quickly by site or operating staff without the need for specialists ; in this way, the dam is more or less permanently monitored, and the records are available for statistical analysis.

3.4 In recent decades far more attention has been focused on deformations and hydraulic behaviour in the foundations.

3.5 Il faut souligner le rôle irremplaçable de la surveillance visuelle du barrage et de ses abords, effectuée par des personnes connaissant bien l'ouvrage, en vue de déceler des anomalies qui ne seraient détectées par aucun dispositif aussi complet et sensible qu'il soit : fissures et fuites, dégradation locale du matériau, extension des taches d'humidité,...

3.6 Le choix des paramètres significatifs du comportement d'un barrage, à mesurer au cours de sa construction et de sa première mise en eau, ainsi que la localisation des appareils de mesures dans l'ouvrage, ne peuvent pas toujours être optimaux.

Le nombre des appareils peut parfois surprendre par son importance au moment de la construction. Il se justifie par la nécessité d'assurer une surveillance aussi efficace que possible sur un ouvrage dont on ne connaît pas encore le comportement.Il faut également tenir compte d'un certain taux de défaillance et aussi de la redondance de certains appareils nouveaux à l'essai.

L'optimisation du dispositif (abandon de certaines mesures, parfois mise en place d'appareils complémentaires) se fait ensuite au fur et à mesure de l'augmentation des connaissances sur le comportement réel de l'ouvrage.

3.7 A l'expérience, une doctrine s'est donc dégagée : surveiller attentivement, souvent et sans délai, un nombre réduit d'appareils bien situés dans l'ouvrage apparaît plus sûr que la recherche laborieuse et aléatoire d'informations dans une masse importante de résultats et cela, bien que les méthodes modernes de traitement de l'information puissent beaucoup faciliter ce travail.

3.8. La première mise en eau constitue une phase importante et délicate de la vie de l'ouvrage. La première mise en charge sert, en fait, d'épreuve permettant de juger si le barrage est apte à remplir ses fonctions. Bien entendu, les mesures d'auscultation devront être commencées bien avant le début du remplissage afin de bien connaître l'état initial de l'ouvrage ; certaines mesures seront d'ailleurs exécutées en cours de construction en vue de suivre le comportement du barrage proprement dit et de sa fondation sous l'effet de la charge des matériaux.

3.9. L'enregistrement en continu de certains appareils et le traitement automatique des données sont concevables pendant la première mise en eau pour acquérir une grande quantité de données sur une période relativement courte.

En exploitation normale, la phase de calcul permettant de passer des lectures des appareils aux grandeurs interprétables est également fortement automatisée.

Par contre "l'automatisation complète du contrôle", c'est-à-dire la transmission automatique, à distance, du niveau de sécurité de l'ouvrage et, le cas échéant, de l'alerte, n'a pas été retenue pour les barrages d'EDF. La délicate fonction d'interprétation fine des comportements des ouvrages appartient à l'ingénieur.

3.5 Visual inspection of dams and surroundings by people who know the dam is very important because even the best instruments will not find fissures, leakages, damp spots or their growth, etc.

3.6 The choice of parameters to be measured and the positioning of instruments cannot always be optimal at the design stage.

The number of instruments sometimes amazes but is justified by the need for effective monitoring of an as yet unfamilar structure.

A proportion of instruments will fail and some redundancy is needed if new types of instrument are installed on a trial basis.

Optimisation of the system can be made by abandoning some instruments or installing others as the real behaviour becomes better understood.

3.7 Although modern information processing can help with the processing of huge masses of raw data, experience has shown that it is a good policy to read often a limited number of key instruments very well situated in the dam.

3.8 The first filling of a reservoir is a stage in its life that is both important and delicate. It is in fact the proof that a dam can fulfil its design functions. Of course, measurements must start earlier so that the structure's initial state is known and some instruments are read during construction so that the reaction of dam and foundation to loading are known.

3.9 Continuous reading of some instruments is conceivable during first filling to obtain a large amount of information during this fairly short period.

During normal operation the raw data is processed by computer to give useful information.

However complete automation - the automatic transmission of the state of safety of a dam and possibly of danger signs - is not used by EDF. The delicate task of fine interpretation belongs to the engineer.

4. *PARAMETRES SIGNIFICATIFS DU COMPORTEMENT DES BARRAGES ET CHOIX DES APPAREILS DE MESURES - EVOLUTION DE LA CONCEPTION DES DISPOSITIFS D'AUSCULTATION AU COURS DE CES DERNIERES ANNEES*

Nous distinguerons les barrages en béton et les digues en remblai et, à l'intérieur de ces deux grandes catégories, les divers types qui s'y rattachent.

Nous indiquerons les paramètres significatifs du comportement du barrage et les dispositifs de mesures correspondants, en soulignant l'évolution qui s'est manifestée dans la conception de ces dispositifs au cours de ces dernières années.

Cette évolution résulte, en grande partie, des enseignements tirés des mesures exécutées sur les ouvrages en service et des progrès réalisés dans les appareils et méthodes d'auscultation.

Il faut également indiquer que, depuis quelques années, le développement des modèles de calcul des barrages, en particulier des digues en remblai, a créé un rôle auxiliaire mais important, qui est l'acquisition de données pour la comparaison des résultats des modèles avec ceux des mesures. Cela pourra conduire, pour certains barrages, à une exigence nouvelle en matière d'auscultation, qui est la connaissance des valeurs absolues des paramètres mesurés (déplacements, pressions interstitielles, contraintes...), alors que la connaissance de l'évolution de ceux-ci suffit le plus souvent pour le contrôle de la sécurité de l'ouvrage.

Nous soulignerons, dès maintenant et une fois pour toutes pour ne pas y revenir par la suite, le rôle important et irremplaçable joué par les mesures de fuites et les observations visuelles des barrages et de leurs abords dans la surveillance de tous les types de barrages.

4.1 Barrages en béton

Les principaux paramètres du comportement des barrages en béton, ainsi que les appareils retenus pour leurs mesures, sont donnés ci-après.

4.1.1 Barrages-voûtes

Il s'agit sans doute du type de barrage où l'évolution de l'auscultation a été la plus marquée.

4.1.1.1 Déplacements du barrage

D'une manière générale, le paramètre "déplacement du barrage" est considéré comme l'un des plus significatifs du comportement d'un barrage en béton : les effets de la charge d'eau, de la température, du retrait du béton, de son fluage sous contrainte, de l'adaptation des fondations, se traduisent par des déplacements de l'ouvrage.

a) Mesures topographiques

Pour mesurer les déplacements des voûtes proprement dites, on a tout d'abord utilisé des méthodes topographiques, essentiellement planimétriques, mettant en oeuvre des appareils précis.

4. SIGNIFICANT PARAMETERS AND CHOICE OF INSTRUMENTS.RECENT DEVELOPMENTS IN MONITORING DESIGN

Concrete dams and fill dams are discussed separately.

The significant behaviour parameters and recent developments in the design of relevant instruments as a result of dam operation and monitoring experience are described.

The development of mathematical models, particularly for fill dams, has given rise to a subsidiary objective, that of collecting performance data for comparison with predicted behaviour. This leads to a need for absolute values for displacements, pore pressures, stresses, etc., whereas only changes or trends in these parameters are usually enough for safety assessment.

We underline once and for all the vital importance of leakage measurement and visual inspection of all types of dams and their surroundings. This remark will not be repeated but should be borne in mind throughout this report.

4.1 Concrete dams

The main performance parameters relevant to concrete dams and the appropriate instruments are discussed.

4.1.1 Arch dams

This is surely where monitoring has undergone the most development.

4.1.1.1 Displacements

Displacement is considered to be one of the most important aspects of the behaviour of a concrete dam. This may come from water loading, temperature effects, shrinkage, creep or adaptation of the foundation.

a) Optical survey

Optical (usually plane) surveying techniques were the first method of dam displacement monitoring.

La méthode le plus souvent appliquée est celle de la triangulation (méthode des intersections), des mesures angulaires étant exécutées sur des repères du barrage à partir de piliers topographiques implantés à l'aval du barrage. De tels dispositifs existent sur de nombreux barrages.

L'apparition, sur le marché, d'appareils électro-optiques de mesures des distances (géodimètres) rend possible la substitution de mesures de distances aux mesures angulaires, la "trilatération" remplaçant alors la méthode des intersections pour la détermination de la position des repères contrôlés. La relative indépendance de l'erreur de détermination par rapport à la distance facilitera le choix des points de référence stables en dehors de la zone d'influence de l'ouvrage, ce qui présente un avantage comparativement à la méthode de triangulation. Cette nouvelle méthode de "trilatération" paraît prometteuse, bien que sa généralisation se heurte encore à quelques difficultés pratiques liées, par exemple, à l'emploi obligatoire de réflecteurs plus complexes, fragiles et chers que les repères topographiques traditionnels. Elle n'a pas reçu, à ce jour, en FRANCE, un grand développement.

L'inconvénient majeur de ces méthodes topographiques est d'entraîner l'intervention d'équipes spécialisées, dans des conditions d'accès irrégulières (notamment en haute montagne), avec mise en oeuvre d'appareils de haute précision. De plus, en ce qui concerne la méthode des intersections, il est nécessaire de contrôler régulièrement la stabilité des stations d'observations par rapport à des repères fixes.

C'est pourquoi on a préféré s'orienter, depuis 1965 environ, vers l'auscultation par un réseau de pendules directs (voûte) et inversés (fondation).

La topographie est seulement retenue pour les voûtes très minces où il n'est pas possible de réaliser des puits et galeries pour l'installation de pendules.

b) Pendules

Le pendule présente toutes les qualités exigées des appareils d'auscultation et indiquées au chapitre 3 ci-dessus : fiabilité, sensibilité, simplicité. Des lectures fréquentes, d'une précision de l'ordre de ± 0,1 mm peuvent être effectuées, en toute saison, par le personnel d'exploitation sur place.

Dans une voûte suffisamment épaisse pour permettre, lors du projet, de prévoir un réseau de puits verticaux et de galeries horizontales (ou inclinées), des pendules directs y seront installés donnant les déformations de l'ouvrage à différents niveaux.

Les files verticales de pendules directs seront prolongées dans la fondation par des pendules inversés, dont les points d'accrochage sont situés à des profondeurs où les mouvements induits par le barrage sont suffisamment amortis et constituent ainsi des points de référence.

Le dispositif de lecture mis au point par EDF est matérialisé par une table, type à "pointes de visée", les lectures d'alignement du fil du pendule sur les deux pointes étant faites sur deux verniers coulissant sur la table et comportant chacun un oeilleton de visée.

Le pendule se prête parfaitement à la télémesure, la télétransmission des lectures à distance pouvant présenter de l'intérêt, par exemple pour les barrages d'accès difficile en hiver.

The commonest method is triangulation on targets on the dam from downstream stations and many dams are so equipped.

The appearance on the market of electronic distance measuring devices allows "trilateration" to be substituted for triangulation. This has the advantage that errors are relatively independent of distance and so stable reference points, outside the zone of influence of the dam, are easier to find. There are however still some difficulties related to, for example, complex, fragile and expensive reflectors. The method appears promising but is not yet in general use in France.

The principal difficulty with survey methods is access for skilled teams in difficult country with precision instruments, especialy at mountain sites. Added to this, it is necessary to check the observation stations against other stable reference points.

Hence, since about 1965, direct (in the arch) and inverted (in the foundation) pendulums have had preference.

Surveys are only used for thin arches where the shafts and galleries needed for pendulums cannot be incorporated in the structure.

b) Pendulums

These possess all the properties required of instruments described in chapter 3 - reliability, sensitivity, simplicity. Frequent readings to an accuracy of 0.1mm can be made, in any weather, by resident operating staff.

Where the dimensions of the arch dam can accomodate a system of galleries and shafts, direct pendulums are installed to measure deformations at different levels.

Inverted pendulums are installed in the foundations. The anchorage points have to be deep enough to be unaffected by the dam.

EDF has standardized on a readout unit consisting of a table with two sighting points and two optical verniers with eye holes.

Pendulums can easily be read remotely and readings can be transmitted if necessary, for example for dams where access is difficult in winter.

Deux types de télépendule ont été mis au point en FRANCE :

- le modèle optique : l'image du fil du pendule est projetée à l'aide d'un objectif photographique sur un réseau de photo-diodes. Deux ensembles objectif-réseau, dont les axes sont orthogonaux, permettent de repérer le fil dans un plan ; un récepteur donne directement les résultats sous la forme de valeurs numériques des coordonnées du fil.

- le modèle inductif : ici, les déplacements du fil sont mesurés dans deux directions à l'aide de capteurs inductifs.

Ces deux types de télépendule permettent une télétransmission aisée des lectures.

4.1.1.2 Déformations unitaires (contraintes) du béton

A l'origine, le calcul des barrages-voûtes était conduit suivant des méthodes moins précises qu'aujourd'hui et l'auscultation cherchait surtout à s'assurer que les niveaux des contraintes en différents points de l'ouvrage ne dépassaient pas des valeurs susceptibles de provoquer des désordres dans le béton.

En complément du jaugeage des fuites en fondation et des mesures topographiques des déplacements des voûtes en quelques points, on s'orientait le plus souvent, pour ce type de barrage, vers une surveillance analytique à base d'un réseau très étoffé d'extensomètres du type "à corde vibrante". En fait, l'emploi de ces appareils, dont il faut reconnaître cependant les bonnes sensibilité et fiabilité, ne permettait pas de connaître, en valeur absolue, le niveau des contraintes atteint, du fait de l'extrême complexité du comportement physico-chimique du matériau, excluant l'emploi de relations simples entre déformations unitaires et contraintes. Par contre, le suivi des mesures permettait de vérifier l'évolution du comportement de l'ouvrage et de déceler d'éventuelles anomalies.

Les progrès réalisés, au cours de ces dernières années, dans les méthodes de calcul des barrages-voûtes (méthode des éléments finis tridimensionnels - relaxation des contraintes de traction dans le rocher de fondation) ont entraîné une bien meilleure connaissance des niveaux de sécurité vis-à-vis des contraintes engendrées par les différents cas de charge.

Il n'était donc plus nécessaire d'aborder la question de l'auscultation des voûtes en terme de contraintes.

L'utilisation d'extensomètres ne serait utile que dans les cas d'incertitudes dans les hypothèses de calculs, d'ouvrages de conception nouvelle, ou d'application de nouvelles méthodes de calculs, en vue de vérifier les résultats.

4.1.1.3 Déformations de la fondation

L'importance du comportement de la fondation (dont il est nécessaire d'élargir la notion au massif supportant la superstructure) pour la tenue de l'ouvrage justifie une surveillance d'autant plus utile que malgré les investigations qui peuvent avoir été faites ses caractéristiques précises sont rarement connues dans leur intégralité.

Les déformations d'un appui rocheux sont en général faibles : si l'on veut mettre en évidence l'amorce d'un mouvement dangereux, il faut disposer

This is done by one of two types of "telependulum" in France :

- optical type. The image of the wire is projected by two orthogonal systems of lenses and photo diode arrays and the receiver gives the numerical values of the wire coordinates directly.

- induction type, in which wire movements are measured by sensors in two planes.

Both types are suitable for remote readouts.

4.1.1.2 Strains (stresses) in concrete

Originally, design analysis for arch dams used to be far less precise than now. Instrumentation was therefore designed to verify that stress levels in the structure remained within limits that would not cause distress to the concrete.

In addition to gauging seepage and measuring movements by optical survey, one generally aimed at analytical monitoring based on a dense network of vibrating wire strainmeters. Because the extremely complex physical and chemical behaviour of the material did not permit a simple stress-strain relationship, these measurements did not give absolute stress values. The series of measurements did however allow a good idea of behaviour trends and the detection of anomalies.

Recent advances in analytical methods, such as three-dimensional finite element and no-tension foundation models, give a better understanding of safety levels under the different load combinations.

It is no longer therefore necessary to address the instrumentation of arch dams in terms of stresses.

Strainmeters now would only be useful as a check in cases of uncertainty in the design assumptions, for innovative designs or where new methods of analysis have been used.

4.1.1.3 Foundation deformations

The importance of foundation behaviour in the performance of the structure justifies study, all the more necessary because rock properties are seldom completely known.

Deformation in rock are normally small, hence to recognise the start of a d'appareils précis. Par ailleurs, l'existence fréquente de discontinuités naturelles ou occasionnées par le fonctionnement de l'ouvrage lui-même (desserrage amont, serrage aval d'appuis de voûte, par exemple) et la nécessité de localiser les mouvements éventuels donnent beaucoup d'intérêt à des appareils fournissant des indications, sinon continues, du moins avec un pas de mesure réduit.

Le pendule inversé cité précédemment permet de connaître le déplacement de la base du barrage au niveau de la fondation.

Pour la mesure des déplacements relatifs en plusieurs points de la fondation, on peut penser à des barres ou des fils de fondation. Mais l'expérience a montré que des difficultés, liées vraisemblablement aux frottements entre fils et à l'imperfection des ancrages, rendaient délicat l'emploi de tous dispositifs pour des mesures à différentes profondeurs dans un même trou de sondage.

Des appareils sont maintenant fabriqués, permettant une investigation quasi continue, sans aucune liaison mécanique, ni frottement entre l'appareil et le forage, tels le "distofor" et "l'extensofor".

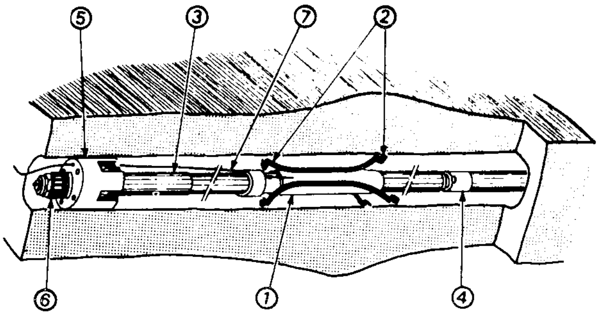


Fig. 1

Distofor.

Distofor.

(1) Bague métallique.	*(1) Reference ring.*
(2) Ressorts d'ancrage au sol de la bague.	*(2) Anchor springs.*
(3) Tige.	*(3) Central rod.*
(4) Raccord étanche.	*(4) Watertight coupling.*
(5) Tête.	*(5) Flush head.*
(6) Connecteur étanche.	*(6) Sealed outlet.*
(7) Dispositif de libération du ressort.	*(7) Anchor spring release.*

dangerous movement one must have very precise devices. Also frequent discontinuities, either natural or caused by loading (e.g. tension cracks upstream or compression downstream of an abut ment), and the need to locate any movement suggest instruments giving readings that, if not spatially continuous,are at least at reasonably close spacing.

The inverted pendulum gives the movement of the base of the dam. For measurements within the foundation, trouble has been experienced with anchoring several bars or wires in a single borehole, apparently because of poor anchorage or friction.

Modern instruments yield a near-continuous log of movements along the borehole with no friction between the sensor and the borewall. Two such are : the Distofor and the Extensofor.

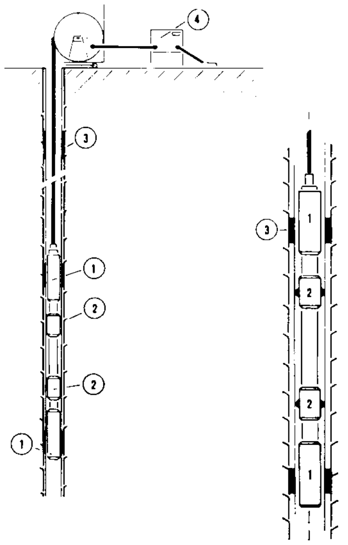


Fig. 2

Extensofor.

Extensofor.

(1) Capteurs.	*(1) Sensors.*
(2) Dispositif de centrage.	*(2) Packers.*
(3) Bagues métalliques.	*(3) Reference rings.*
(4) Poste de lecture.	*(4) Readout set.*

a) Le distofor

L'appareil, dont un schéma est indiqué figure 1, se présente sous la forme d'une canne formée d'éléments assemblés par des raccords étanches; elle est mise en place dans un forage et ancrée à l'une de ses extrémités. La canne comporte un certain nombre de capteurs de déplacements basés sur un procédé utilisant le phénomène de résonance de deux circuits électromagnétiques coaxiaux : un circuit extérieur formé d'un solénoïde, un circuit intérieur résonant formé d'un autre solénoïde et d'une capacité. Tout déplacement relatif des deux circuits modifie l'inductance du circuit intérieur et par conséquent sa fréquence d'oscillation qui est la grandeur mesurée et qui est reliée directement au déplacement cherché.

La précision pratique in situ est meilleure que 1/10 mm. Une même canne peut porter un grand nombre de capteurs.

Depuis quelques années, des applications nombreuses à l'auscultation des barrages ont été réalisées.

b) L'extensofor

Cet appareil utilise les mêmes capteurs électromagnétiques que le distofor, mais il s'agit cette fois d'une sonde mobile introduite dans le forage chaque fois que l'on veut faire une mesure (Fig. 2)

4.1.1.4 Sous-pressions dans les fondations

Les mesures des pressions d'eau dans les fondations revêtent une grande importance liée non seulement à la connaissance qu'elles apportent sur les forces d'origine hydraulique agissant sur tout ou partie des fondations, mais aussi à la compréhension qu'elles améliorent du fonctionnement hydraulique de l'ouvrage.

C'est ainsi que les mesures de ces pressions, associées aux mesures des débits de fuites, facilitent l'interprétation de ces dernières ; elles sont donc complémentaires.

Les drains qui sont normalement installés dans les fondations, comme moyen d'action corrective vis-à-vis des sous-pressions, sont d'excellents moyens d'auscultation. Mais l'interprétation de leur variation n'est le plus souvent possible qu'avec l'aide des mesures piézométriques : par exemple, dans le cas d'une diminution des débits de drains de fondation, une diminution des sous-pressions indique un colmatage amont, une augmentation des sous-pressions une perte d'efficacité des drains.

Il faut également souligner que les mesures de fuites, si elles sont convenablement organisées, ont un caractère synthétique, alors qu'une mesure piézométrique est au contraire localisée et ne donne une indication que sur la zone entourant le capteur considéré.

La piézométrie dans une fondation rocheuse dépend de nombreux facteurs: réseau de fissures, hétérogénéités (diaclases), efficacité des rideaux d'injection et de drainage. Un réseau de piézomètres ne peut être installé avec efficacité dans un appui rocheux qu'à condition de bien connaître sa structure ; il sera d'ailleurs souvent nécessaire de compléter le réseau après la première mise en eau, une fois mieux connue l'hydrogéologie de l'appui.

a) Distofor

This is shown in figure 1. The central rod lengths are assembled with watertight couplers and anchored to the rock at hole collar or bottom. Each sensor consists of an outer solenoid and a concentric solenoid and capacitor inside it, forming a resonant circuit. Relative movements change the inductance of the inner circuit, and thereby the output frequency. This frequency is measured and is related directly to displacement.

In situ precision is better than 0.1 mm. Multiple sensors can be fitted to the same rod.

The Distofor has been installed in many dams in recent years.

b) Extensofor

This is similar to the Distofor and uses the same electromagnetic principle. The device is mobile and is lowered into the borehole each time a reading is taken (Fig. 2).

4.1.1.4 Uplift pressures in foundations

Water pressure measurements in the foundation are important not only to measure pressures but also to give an understanding of hydraulic behaviour of the structure. They also complement the gauging of seepage water. For instance, a reduction in the flow from foundation drains could be caused by sealing of the upstream foundation or by blockage of the drains and flow measurement alone would not tell which : in the first case, the pressure drops, in the second case, the pressure rises. On the other hand, properly organised seepage measurement gives a far wider picture than piezometers which are representative of only small zones round the instruments themselves.

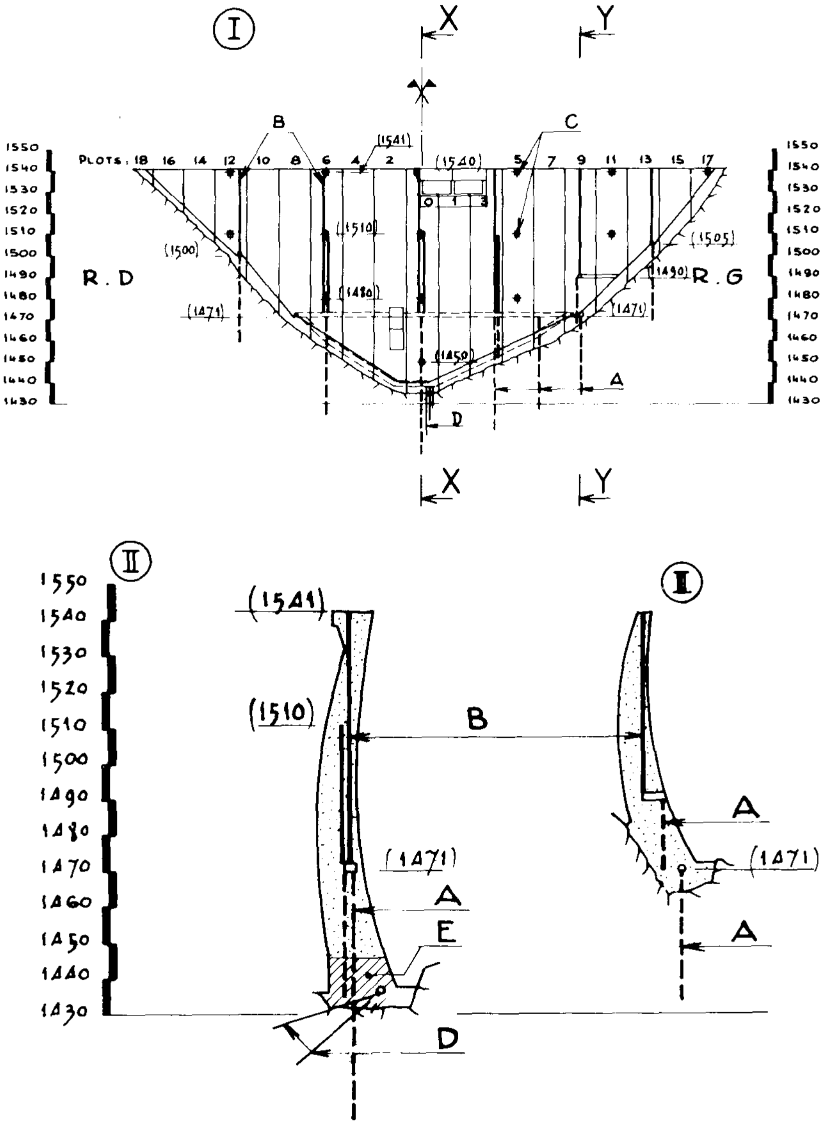


Fig. 3

Barrage-voûte de Laparan — Dispositif de mesures des déformations

Laparan arch dam — Deformations measurements

I. Elévation aval	*I. Downstream view*
II. Coupe X-X	*II. Cross section X-X*
III. Coupe Y-Y	*III. Cross section Y-Y*
A. Pendule inversé	*A. Inverted pendulum*
B. Pendule direct	*B. Direct pendulum*
C. Repère topographique	*C. Survey points*
D. Extensomètre en forage	*D. Extensometer in borehole*
E. Zone équipée d'extensomètres dans le béton	*E. Concrete zone with extensometers*

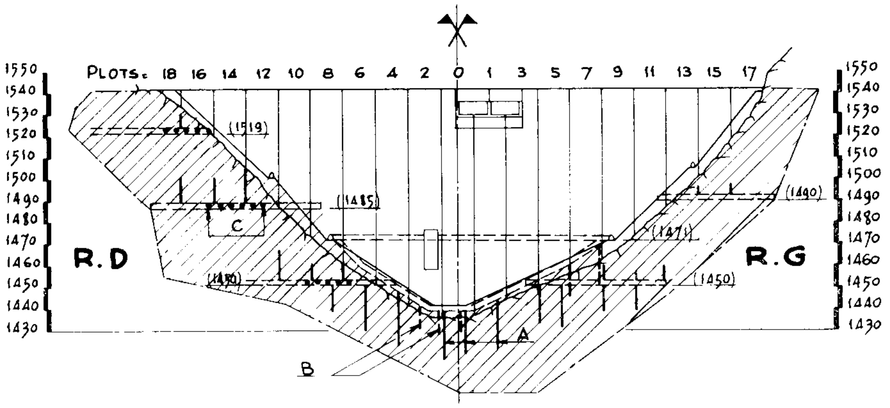


Fig. 4

Barrage-voûte de Laparan — Dispositif de mesures piézométriques

Laparan arch dam — Piezometric measurements

A. Piézomètres profonds	*A. Deep piezometers*
B. Piézomètres courts	*B. Short piezometers*
C. Piézomètres subhorizontaux	*C. Horizontal piezometers*
Zone hachurée : Voile d'injection	*Hachured area : Grout curtain*

La valeur des résultats de mesures piézométriques dans une fondation rocheuse est souvent altérée par la mauvaise disposition des chambres de mesures. C'est ainsi qu'une chambre de mesures trop longue donne une moyenne erronée, en mettant en communication des niveaux de piézométrie différente. Des chambres de mesures réduites - longueur de l'ordre de 1 à 2 m - sont à retenir.

4.1.1.5 Exemple : dispositif d'auscultation du barrage-voûte de Laparan (EDF)

Il s'agit d'une voûte à double courbure, de 106 m de hauteur sur fondation et de 280 m de longueur en crête, qui vient d'être achevée dans les Pyrénées. La fondation du barrage est constituée d'un gneiss très rigide, coupé par divers accidents.

En aval du voile d'étanchéité, le rocher est drainé par 5 galeries avec forages drainants.

Le dispositif d'auscultation, mis en place sur ce barrage par EDF, est caractéristique des nouvelles tendances (Fig. 3 et 4) :

a) dispositif définitif

- 19 pendules (dont 7 pendules inversés en fondation) répartis sur 7 profils

- des mesures piézométriques en fondation : piézomètres, à chambre de mesure courte (2 m)

- des mesures de fuites (dans les galeries de fondation)

b) dispositif provisoire

- un dispositif topographique (de construction de l'ouvrage) permettant lors de la première mise en eau de mesurer les déplacements de repères scellés sur le parement aval de la voûte.

- deux extensomètres en forage (un fil de fondation et un distofor), installés à la base de la console de clé, pour étudier le comportement du rocher de fondation dans la zone amont.

- quelques extensomètres noyés dans le béton, à la base de la voûte, pour vérifier les contraintes dans cette zone.

4.1.2 Barrages-poids

Le dispositif d'auscultation de ce type de barrage est classique depuis de nombreuses années ; il comprend essentiellement :

- des lignes de pendules directs et inversés. Le pendule est en effet mieux adapté que les dispositifs topographiques à la mesure des faibles déplacements de ce type de barrage.

- des appareils de contrôle des mouvements des joints entre plots (dans les 3 directions)

- des piézomètres en fondation : les remarques faites à propos de ces appareils au chapitre 4.1.1.4. ci-dessus sont valables ici.

Foundation pressure measurements depend on many things such as the joint spacing, faults and effectiveness of drainage and grout curtains. A piezometer network cannot be usefully installed in rock without knowing its structure. Moreover, it will often be necessary to augment the network after first filling when the hydrogeology is better understood. Measurement chambers should be fairly short (1-2 m) so that they do not connect two areas with different pressures and so give a misleading average.

4.1.1.5 Example : LAPARAN dam (EDF)

This is a double curvature arch dam 106 m high and 280 m long, just finished in the Pyrénées. The foundation is very hard gneiss cut by various faults. Downstream of the grout curtain there are 5 drainage galleries with drilled drains.

The instrumentation system put in by EDF is typical of modern practice (Fig. 3 and 4) :

a) permanent system

- 19 pendulums of which 7 are inverted, on 7 sections
- foundation piezometers with short (2 m) measurement chambers
- seepage measurement in the foundation galleries.

b) temporary system

- survey network (used to allow measurement of movement of targets on the downstream face of the dam during first filling)
- two borehole extensometers (one wire, one Distofor) at the base of the crown cantilever to study upstream rock behaviour
- a few embedded strainmeters in the concrete, at the foot of the arch, to check stresses in this area.

4.1.2 Gravity dams

Instrumentation of this type of dam has not changed for many years and consists mainly of :

- lines of direct and inverted pendulums. The pendulum is far better than survey methods for measuring the very small movements in this type of dam
- movement measurement at joints (in 3 directions)
- foundation piezometers. The remarks in 4.1.1.4 are applicable.

Des fils de fondation peuvent être envisagés pour surveiller la décompression du pied amont : ils seront plutôt verticaux qu'horizontaux (une utilisation des fils des pendules inversés est envisageable pour un tel contrôle).

Pour ce type de barrage, il faut signaler l'abandon des clinomètres, de type niveau optique de mécanicien, de haute précision, utilisés pendant quelque temps. Ces appareils étaient mis en place sur des plaques de base, de faible diamètre, liées aux structures. De nombreuses difficultés d'interprétation des résultats sont apparues, les causes essentielles étant : d'une part, la taille réduite de la base de mesure comparativement à celle des structures à surveiller, ce qui rend les mesures non représentatives d'un comportement d'ensemble, d'autre part, l'existence de problèmes de scellement des plaques de base.

4.1.3 Barrages à contreforts, barrages à voûtes multiples

La grande variété des barrages de ce type ne permet pas de donner des indications précises sur la conception de leur auscultation.

On peut simplement indiquer que les contreforts se prêtent généralement bien à l'installation des pendules, tandis que les voûtes multiples justifient le plus souvent l'emploi de dispositifs topographiques de mesures planimétriques.

Des mesures de tassements au pied des contreforts pourront également être retenues.

Dans certains cas particuliers (taux de contrainte élevé, conception nouvelle), une auscultation des contreforts et des voûtes multiples, par extensomètres, peut présenter de l'intérêt.

4.1.4 Barrages mobiles

La modification des conditions de stabilité des barrages mobiles, parfois fondés sur des terrains très déformables, se traduit le plus souvent par des inclinaisons des plots.

Aussi, l'auscultation de ce type de barrage au moyen :

- de pendules situés dans les piles, une galerie de visite horizontale dans le radier permettant les lectures,

- de mesures de nivellement topographique sur des repères scellés à la partie supérieure des piles et dans la galerie du radier,

est-elle à recommander.

Ce dispositif de mesures des mouvements sera le plus souvent complété par un dispositif de mesures piézométriques dans la fondation, sous le radier : piézomètres dans une fondation rocheuse, cellules de pression interstitielle dans une fondation meuble.

Wires in the foundation may also be considerd to measure the heave at the upstream heel. These should be vertical and the measurements could be made with the inverted pendulums.

The abandonment of precision optical bubble levels (clinometers) should be noted. Difficulties occurred with interpretation, the main causes being the smallness of the base in comparison with the main structure resulting in measurements being unrepresentative, and problems with fixing the bases.

4.1.3 Buttress and multiple arch dams

The great variety in this type of dam does not permit any precise statement on the design of their instrumentation systems.

One can only say that buttresses lend themselves to pendulums while multiple arches are better adapted to survey methods.

Settlement measurements at the feet of buttresses can also be made.

In particular cases such as highly stressed dams or novel design, strainmeters in the buttresses and multiple arches would be useful.

4.1.4 Gated barrages

Change in stability conditions with this type of dam, sometimes founded on deformable ground, usually shows itself by the tilting of monoliths. Hence the following instrumentation is recommended :

- pendulums in the piers and a horizontal access gallery in the apron for reading them

- levelling on bench marks fixed to the upper part of the piers and in the gallery.

There will also often be water pressure measurements in the foundation under the apron (piezometers in rock, pore pressure cells in soil).

4.2 Barrages en terre et en enrochement

Comparativement aux barrages en béton, d'autres paramètres vont intervenir pour définir le comportement des digues en remblai, en raison même des matériaux, terre et enrochement, constituant ces ouvrages.
Les principaux paramètres du comportement des barrages en terre et en enrochement, ainsi que les appareils retenus pour leurs mesures, sont donnés ci-après.

4.2.1 Déplacements de surface

Compte tenu de l'amplitude des déplacements de surface (plusieurs cm), les méthodes topographiques (méthode planimétrique des intersections et méthode de nivellement direct) sont parfaitement adaptées à leurs mesures.

Pour l'auscultation topographique de ces digues, les repères à viser sont en général scellés sur des poutres en béton qui devront être suffisamment enfoncées dans le remblai pour ne pas traduire seulement les mouvements des matériaux de surface.

Dans le cas des digues à masque amont, une attention spéciale sera portée à la mesure topographique des déformations de l'organe d'étanchéité.

4.2.2 Déformations internes

La connaissance des déformations internes des digues en remblai et leur évolution dans de temps présentent également un grand intérêt pour juger du comportement de ces digues.

Il s'agit, tout d'abord, des mesures des tassements internes.

Pour ces mesures, la préférence va aux dispositifs horizontaux de mesures, plus aisés à mettre en place et, a priori, moins susceptibles d'être à l'origine de désordres éventuels que les dispositifs verticaux, type "cross-arms".

Le dispositif le plus couramment utilisé sur les barrages français est le téléniveau hydraulique, utilisant le principe des vases communicants entre l'extérieur (point de référence) et un point noyé dans le remblai (mesure ponctuelle) ou mobile dans un conduit horizontal noyé dans le remblai (dispositif appelé "furet hydraulique" et permettant des mesures en plusieurs points du conduit).

Les mesures de déformations verticales peuvent, dans certains cas, être complétées par des mesures de déformations longitudinales suivant des horizontales : par exemple, contrôle des mouvements de remblais placés sur des versants rocheux de pente raide. Pour ces mesures, on dispose :

- d'élongamètres, à longues bases, utilisant la corde vibrante ou des capteurs à induction pour la mesure des variations de longueur,

- de sondes électromagnétiques : tubes "horizontaux" entourés de plaques métalliques annulaires ancrées dans le remblai, dont les variations de distance sont mesurées au moyen d'une sonde électromagnétique. Un tel dispositif peut être associé à un furet hydraulique de mesure des tassements.

4.2 Earth and rockfill dams

Different parameters to those for concrete dams are measured because of the very different materials of which these dams are made.

4.2.1 Surface movements

Because of the size of the deformations (several cm) survey methods (plane triangulation and direct levelling) are suitable.

Targets are usually fixed to concrete beams sunk deep into the fill.

For dams with upstream facing, special attention must be given to topographic measurement of deformations of the facing.

4.2.2 Internal deformation

Knowledge of internal deformations and their changes with time is extremely important for judging the behaviour of a fill dam.

First is internal settlements. For these, horizontal measurements devices are preferred, being easier to place and a priori less likely to cause problems than the vertical, cross-arm type.

The apparatus most commonly used in France is the hydraulic level. Basically a water-filled container buried in the dam connects with a transparent standpipe at the face, so that the level of the free water surface can be read. An alternative has a torpedo moving along the connecting tube to obtain a more continuous profile (known as the "hydraulic ferret").

Horizontal movements are also sometimes measured in the longitudinal direction, for example in fills placed against steep rock slopes. For these there are :

- long extensometers using vibrating wire or induction sensors.

- electromagnetic torpedoes in horizontal tubes passing through metal plates fixed in the fill, which are located by the electromagnetic sensor. They may be combined with hydraulic ferrets.

4.2.3 Pressions hydrauliques internes dans les remblais

Constituées de matériaux plus ou moins perméables, les digues en remblai (et leurs fondations) sont, dans tous les cas où l'étanchéité du parement amont n'est pas totale, le siège d'écoulements permanents ou transitoires dont les caractéristiques constituent un élément de surveillance très significatif.

Les pressions interstitielles (dues à la consolidation des terres) et les pressions d'écoulement (en relation avec la retenue amont et, le cas échéant, avec le niveau d'eau aval) interviennent, de façon directe, dans la stabilité du massif.

Pour les mesures de pressions hydrauliques internes, on peut diviser les remblais en trois catégories : ceux qui sont suffisamment perméables pour que la distribution des pressions d'eau soit pratiquement hydrostatique et connue par les conditions aux limites (retenue amont, niveau aval), ceux qui sont semi perméables et ceux qui sont pratiquement "étanches". Ce n'est que dans ces deux derniers cas que se pose la question de leur mesure. Le piézomètre consistant en un simple tube d'acier enfoncé dans le remblai ne peut pas convenir à cause des volumes d'eau excessifs qui devraient être mis en jeu pour arriver à un équilibre. On fait donc appel à des cellules de pression interstitielle, comportant essentiellement une "boîte" placée dans le remblai pendant sa construction ou au fond d'un forage. Cette "boîte" devra être pleine d'eau en équilibre de pression avec l'eau extérieure à travers une pierre poreuse.

Deux types de cellules se présentent : les cellules hydrauliques (type USBR) et les cellules "électriques".

Bien que les cellules hydrauliques mises en place sur les digues fonctionnent parfaitement, la préférence, en FRANCE, va maintenant aux cellules "électriques" plus simples à mettre en place et à exploiter et susceptibles de s'adapter sans difficulté aux automates d'acquisition des données.

Dans une cellule électrique, une corde vibrante mesure la déformation d'une enceinte élastique sur laquelle s'exerce la pression d'eau ; le signal est une fréquence transmise par fils électriques.

4.2.4 Pressions hydrauliques internes dans les fondations

Les mesures de pressions d'eau s'imposent aussi dans les appuis des barrages en remblai, constitués en général de roche de qualité plus faible que celle des appuis des barrages en béton ou de terrains meubles.

Si les efforts appliqués par le barrage en remblai sont plus répartis que dans le cas d'un barrage en béton et largement stabilisateurs, par contre les pressions d'écoulement sont susceptibles d'avoir des effets dynamiques (érosion interne) ou chimiques (dissolution des matériaux). Il faut donc les contrôler.

Les éléments donnés dans les chapitres ci-dessus 4.1.1.4. et 4.2.3. sont valables pour ces mesures.

4.2.3 Hydraulic pressures in the fill

There is movement of water, either temporary or permanent, in all fills dams (and their foundations) where the upstream face is not absolutely watertight. The pore pressures caused by earth consolidation and the seepage pressure due to water flow between the reservoir and the tailwater level, directly affect dam stability.

For measuring water pressures, fill dams can be divided into three categories : those that are permeable enough for the pressure distribution to be practically hydrostatic and evident from the upstream and downstream water levels, those that are semi-permeable and those that are virtually watertight. The last two cases often happen and it is in these cases that measurement is necessary.

Simple open pipe piezometers driven into the fill will not work because of the excessive quantities of water that must flow to reach equilibrium. Pore pressure cells must be used, consisting of a "can" filled with water in equilibrium with the external water pressure through a porous stone. They can be placed during construction or in boreholes.

Two types of pore pressure cell are used : hydraulic (USBR type) and electric.

Although hydraulic cells that have been installed work perfectly well, the current preference in France is for electric cells which are easier to place and use, and can easily be adapted for automatic data acquisition.

In this type of electric cell, a vibrating wire measures the deformation of an elastic container, which is exposed to the water pressure through a porous stone. The output signal is a frequency, suitable for transmission by wire.

4.2.4 Hydraulic pressures in the foundations

Water pressure measurements are also needed in the foundations of fill dams which are usually weaker than those of concrete dams.

While the load from the dam is spread over a larger area than at a concrete dam and in general has a stabilizing effect, the seepage pressures may cause erosion or solution of materials.

The contents of 4.1.1.4 and 4.2.3 are applicable to these measurements as well.

4.2.5 Example : GRAND'MAISON dam

EDF's Grand'Maison dam is an earth and rockfill structure, 160 m high and 550 m long. It contains 12.4 million m^3 of which 1.9 million is in the core.

The instrumentation system is fairly dense. As well as dam safety, it is designed to check, during construction and first filling, the results of mathematical models. Of course the number of readings can be reduced after successful first filling.

The instruments are arranged on 9 cross-sections parallel to the axis of the valley (3 principal and 6 secondary) and 4 horizontal sections.

They consist of :

- Survey measurements (horizontal and vertical)

- a set of points fixed to beams in the downstream (83) and upstream slopes (27)

- 25 points on both upstream and downstream sides of the crest to record upstream-downstream extensions and settlements.

- Internal deformation measurements (Fig. 5)

- 9 hydraulic ferrets and electromagnetic distance-measuring devices in the downstream fill

- 9 hydraulic settlement tubes in the downstream fill

- 8 settlement tubes (4 in upstream fill and 4 in the core)

- 6 extensometers (5 in the core and 1 downsteram)

- Pore pressure measurements (Fig. 6)

- Core : 92 pore pressure cells

- Upstream shell and filter : 20 pore pressure cells

- Foundation : 7 piezometers immediately downstream of the grout curtain and 3 downstream of the dam in the alluvial bed. 3 pore pressure cells under the core on both sides of the grout curtain.

All the pore pressure cells are electric.

- Seepage measurements at 7 places

The total seepage is measured.

4.2.5 Exemple : dispositif d'auscultation du barrage de GRAND'MAISON

Le barrage EDF de GRAND'MAISON est un ouvrage en terre et en enrochement, à noyau en terre morainique, de 160 m de hauteur au-dessus du point bas de la fondation et de 550 m de longueur en crête. Le volume des matériaux mis en place est de 12,4 hm^3, dont 1,9 pour le noyau.

Le dispositif d'auscultation retenu est assez dense. En plus du contrôle de la sécurité du barrage, il est apparu également intéressant d'acquérir, pendant la construction et la mise en eau, des données pour la comparaison des résultats des modèles mathématiques avec ceux des mesures sur l'ouvrage réel.

Bien entendu, le dispositif pourra être allégé par la suite, en exploitation normale, au vu du comportement de l'ouvrage pendant sa première mise en eau.

Les appareils d'auscultation sont répartis, d'une part, suivant 9 coupes transversales parallèles à l'axe de la vallée (3 sections principales et 6 sections secondaires) et, d'autre part, suivant 4 coupes horizontales.

Le dispositif comprend :

- Des mesures topographiques (planimétriques et altimétriques)

- un réseau de repères scellés sur des poutres ancrées dans les parements aval (83 repères) et amont (27 repères)

- des repères en crête (25 sur chaque bord) pour mesurer l'étirement amont-aval et les tassements

- Des mesures de déformations internes (Fig. 5)

- 9 "furets" hydrauliques, associés à un dispositif électromagnétique de mesures de distances, dans la recharge aval

- 9 téléniveaux dans la recharge aval

- 8 téléniveaux (4 dans la recharge amont et 4 dans le noyau)

- 6 élongamètres : 5 dans le noyau et 1 dans la recharge aval

- Des mesures de pressions hydrauliques internes (Fig. 6)

- Dans le noyau : 92 cellules de pression interstitielle

- Dans la recharge amont et le filtre amont : 20 cellules

- Dans la fondation : 7 piézomètres à l'aval immédiat du voile d'injection et 3 piézomètres à l'aval du barrage, dans le sillon alluvionnaire - 3 cellules de pression interstitielle dans la section centrale de l'ouvrage, sous le noyau de part et d'autre du voile d'étanchéité.

Toutes les cellules de pression interstitielle sont du type électrique.

- Des mesures des débits de percolation collectés en 7 points

Le débit total est enregistré.

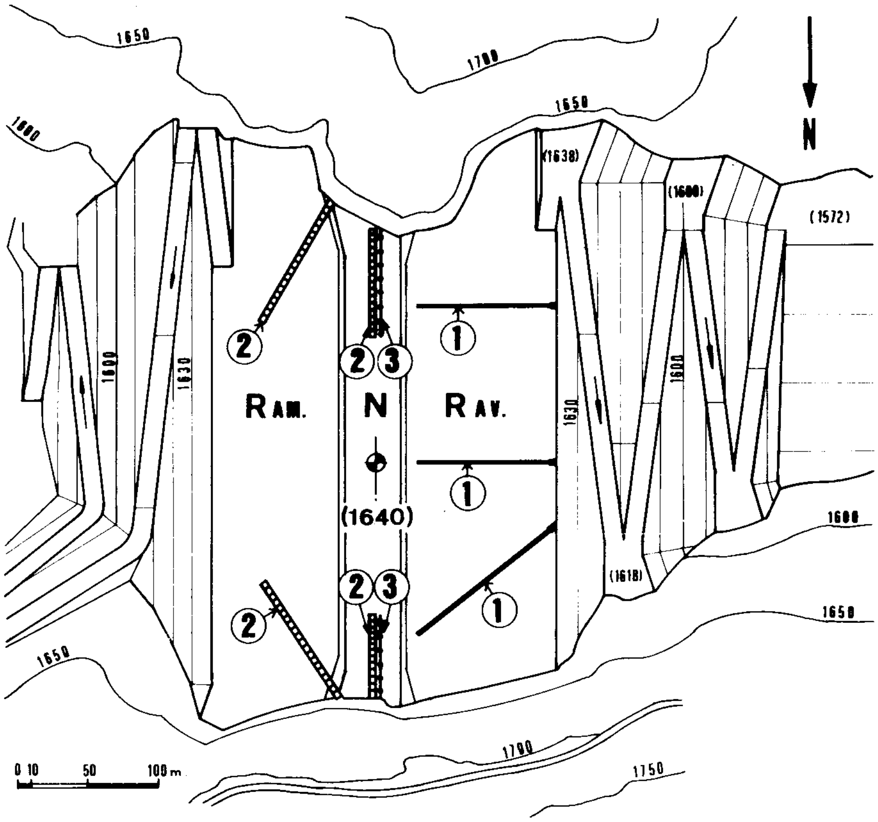


Fig. 5

Digue en terre et en enrochement de Grand'Maison
Appareils d'auscultation au niveau 1 640

Grand'Maison earth and rockfill dam
Instrumentation at elevation 1 640

1. Furets hydrauliques associés à des sondes électromagnétiques, donnant les déplacements verticaux et longitudinaux	*1. Hydraulic settlement gauges and electromagnetic gauges for longitudinal displacements measurements*
2. Téléniveaux électriques donnant les déplacements verticaux	*2. Electric settlement gauges*
3. Elongamètres donnant les déplacements longitudinaux	*3. Electromagnetic gauges for longitudinal displacements measurements*
N. Noyau	*N. Core*
Ram. Recharge amont	*Ram. Upstream shell*
Rav. Recharge aval	*Rav. Downstream shell*

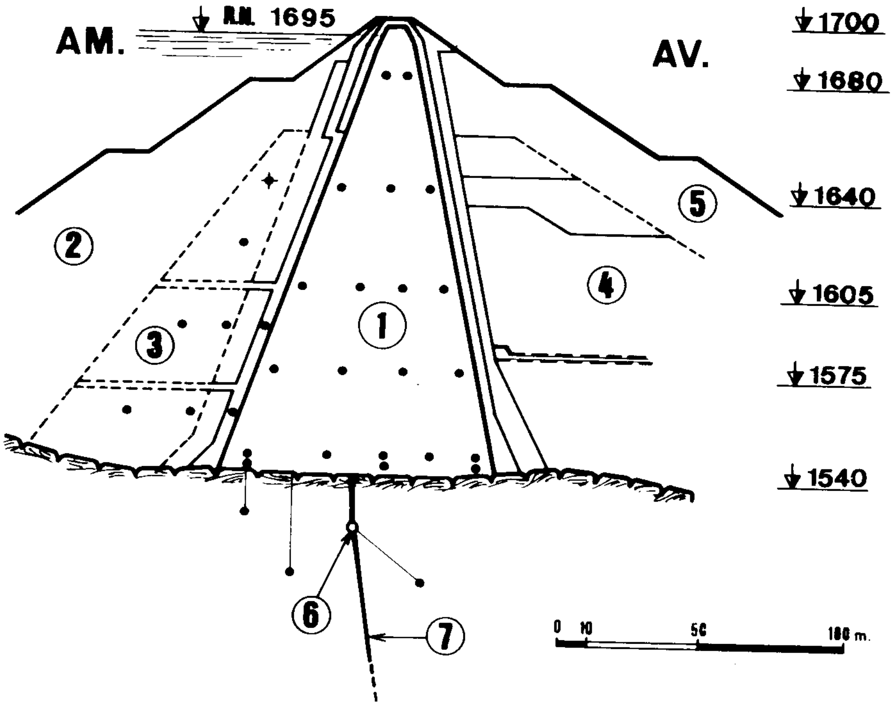


Fig. 6

Digue en terre et en enrochement de Grand'Maison
Cellules de pression interstitielle dans la section centrale du barrage

Grand'Maison earth and rockfill dam
Pore pressure cells in the central cross section

1. Noyau	*1. Core*
2. Enrochements de la recharge amont	*2. Upstream rockfill*
3. Eboulis de la recharge amont	*3. Upstream talus*
4. Eboulis de la recharge aval	*4. Downstream talus*
5. Enrochement de la recharge aval	*5. Downstream rockfill*
6. Galerie périmétrale	*6. Peripheral gallery*
7. Rideau d'injection	*7. Grout curtain*
● Cellules de pression interstitielle	● *Pore pressure cells*

5. AUTOMATISATION DES MESURES D'AUSCULTATION

Le chapitre 3.9 ci-dessus précise la position d'EDF sur la question de l'automatisation : l'automatisation complète du contrôle, c'est-à-dire la transmission, à distance, du niveau de sécurité de l'ouvrage et, le cas échéant, de l'alerte n'a pas été retenue ; la délicate fonction d'interprétation des résultats appartient à l'ingénieur.

Cependant, il faut admettre que la surveillance des barrages doit, comme toute autre activité, utiliser les moyens nouveaux mis à disposition par les progrès technologiques, s'ils lui permettent d'améliorer son efficacité tout en conservant un coût acceptable.

De tels progrès peuvent résulter de l'insertion d'automates d'acquisition des données dans le processus de surveillance des barrages : automatisation des mesures et télétransmission.

L'automatisation pourra avoir une influence sur le choix des appareils, certains se prêtant mieux que d'autres à une telle automatisation : par exemple, télépendules, cellules de pression interstitielle type "électrique".

- Un appareillage de mesure automatique et de télétransmission a été installé sur un barrage-poids EDF, isolé ; il permet la mesure à distance de deux pendules et de deux déversoirs de mesure de fuites. Le dispositif comprend:
. à l'usine, où se trouve en permanence du personnel d'exploitation, un ensemble qui reçoit et affiche les résultats de mesures ; une commande permet à l'exploitant de réaliser, lorsqu'il le désire, la séquence de mesure,
. au barrage, un automate qui gère le déroulement de la séquence et le transit des résultats, deux capteurs "télépendules" et deux capteurs de niveau disposés à l'amont des deux déversoirs de fuite.

- Une expérimentation est actuellement en cours sur les barrages voûtes EDF de TIGNES (hauteur 180 m) et de LAPARAN (voir chapitre 4.1.1.5.), en vue de l'automatisation de l'acquisition et de la transmission à distance d'un ensemble de mesures d'auscultation de ces deux ouvrages : mesures des déplacements (pendules), mesures de pressions (piézomètres), mesures des débits de fuite.
Un poste d'acquisition des données est situé dans le barrage.
Un poste centralisé situé à l'usine la plus proche assure la transmission des demandes exprimées par l'exploitant local ou pour la DTG, la réception des mesures et les traitements locaux nécessaires à l'exploitant pour l'interprétation des résultats bruts. L'exploitant pourra ainsi obtenir un tracé automatique de graphiques des lectures (déplacements, débits de fuite...) en fonction du temps ou de la cote de retenue.
Toutes les mesures sur les appareils pourront être obtenues, soit à partir du poste centralisé, soit à partir du centre de calcul de la DTG (lignes téléphoniques).

Bien entendu, l'existence de tels dispositifs automatiques ne modifie en rien l'organisation qui existait auparavant pour assurer l'interprétation des mesures et les visites périodiques des ouvrages.

5. AUTOMATION OF INSTRUMENT READINGS

The EDF policy on automation is given in 3.9 above : Total automation - remote reading of the safety of the dam and, if necessary, giving the alert - is not used ; the delicate role of measurements interpretation and safety evaluation belongs to the engineer.

However dam inspection, like all other activities, must use available modern means to improve efficiency at acceptable cost. This can result in the use of automatic data acquisition and transmission.

Automation can affect the choice of instruments, for example remotely read pendulums (telependulum) and electric pressure cells.

At one isolated EDF gravity dam, automatic measurement and transmission has been installed for two pendulums and two seepage gauging weirs. The permanently staffed power station receives and displays the data, and the staff can initiate a reading sequence. At the dam, there is a device which controls the scan sequence and transmits the data from two pendulums and two water levels upstream of two weirs.

An automation trial is currently being made on the EDF arch dams at Tignes (180m high) and Laparan (see 4.1.1.5). Displacements are measured (by pendulums), water pressures (by piezometers) and seepage flows. A data acquisition station is located on the dam.

A central post at the nearest power station sends data requested by the dam operators or required by the Regional Monitoring Centre, records instrument readings and does the processing needed by the operators to interpret the raw data. This provides the operators with raw automatically-plotted graphs of displacements, leakage, etc. versus time and reservoir level.

All instrument readings can be obtained from the powerstation post or the Regional Centre by telephone line.

The existence of such automatic devices does not affect in any way the existing organization for interpretation and for site inspection.

6. CAS DES BARRAGES ANCIENS

Ainsi qu'il a été dit précédemment, la réglementation française a prévu, pour les barrages anciens, la possibilité d'engager une procédure de révision spéciale pouvant conduire, en particulier, à la mise en place ou à l'amélioration de dispositifs d'auscultation.

D'une manière générale, les dispositifs d'auscultation installés sur ces barrages anciens seront assez simples, car on demandera surtout à ces dispositifs de détecter les anomalies préoccupantes pour la sécurité des ouvrages et non de fournir un état complet de leur comportement.

Exemple : Les barrages-poids en béton ou en maçonnerie

Pour ces ouvrages, une préoccupation constante a été la mise en place d'un minimum d'auscultation piézométrique dans la fondation et au contact entre le rocher et le béton ou la maçonnerie.

La création ou l'amélioration d'un dispositif de mesure de fuites - et, le cas échéant, du système de drainage - est également recommandée.

En ce qui concerne les déplacements, l'existence de puits et de galeries dans le barrage facilite l'installation de pendules directs. Lorsque ce n'est pas le cas, on peut envisager la réalisation de forages depuis la crête pour la mise en place de pendules inversés ancrés en fondation, avec lecture en crête.

Parfois, le glissement sur sa fondation, accompagné ou non d'un basculement d'ensemble vers l'aval, peut constituer le mécanisme potentiel de ruine d'un barrage-poids. Dans ce cas, des forages extensométriques (distofor), destinés à mesurer les déplacements relatifs du barrage par rapport à sa fondation, constitueront un moyen de surveillance efficace.

7. ANALYSE ET INTERPRETATION DES RESULTATS DES MESURES D'AUSCULTATION AU COURS DE LA CONSTRUCTION, DE LA PREMIERE MISE EN EAU ET DE L'EXPLOITATION NORMALE DES BARRAGES

Deux périodes peuvent être distinguées :

- Période de construction et de première mise en eau
- Période d'exploitation normale

7.1 Période de construction et de première mise en eau

7.1.1 Particularités de l'auscultation au cours de cette période

Le contrôle d'un barrage pendant sa construction (principalement les barrages en remblai) et sa première mise en eau consiste en une observation à peu près permanente des paramètres significatifs du comportement de l'ouvrage.

6. OLD DAMS

As stated earlier, French legislation embodies a special evaluation procedure which provides placing new instruments or improving old ones. Generally speaking, simple instruments are installed in old dams, only to detect dangerous anomalies and not fully to describe the complete behaviour of the dam.

Example : Concrete or masonry gravity dams

A constant worry has been to ensure there are at least some piezometers in the foundation and foundation contact of such dams. Installation or improvement of seepage monitors and, if necessary, a drainage system are also recommended.

For displacements, if there are shafts and galleries, they can be used for direct pendulums ; if not, inverted pendulums can be drilled from the crest, with the readout station at the top.

If the failure mechanism would be by sliding on the foundation with or without tilting, extensometers (Distofor) could be installed to measure the relative movements.

7. ANALYSIS AND INTERPRETATION OF MEASUREMENTS DURING CONSTRUCTION, FIRST FILLING AND NORMAL OPERATION

7.1 Construction and first filling

7.1.1 Peculiarities of monitoring during this period

During construction (of fill dams especially) and first filling, observation of significant parameters is practically continuous. For this, competent personnel, for quick analysis and interpretation, is essential : construction or filling may be slowed or stopped when anomalies are found.

Cette surveillance nécessite la présence sur les lieux d'un personnel compétent, capable d'interpréter correctement et rapidement les résultats des mesures. Un contrôle suivi et efficace ne pourra être exercé qu'en appliquant des méthodes d'analyse et d'interprétation rapides.

Pendant la construction, toute anomalie de comportement du barrage pourra conduire à un arrêt momentané ou à un ralentissement de la mise en place des matériaux, afin d'expliquer cette anomalie.

La première mise en charge d'un barrage constitue une phase importante et délicate de la vie de l'ouvrage. Il sert, en fait, d'épreuve permettant de juger si l'ouvrage est apte à remplir ses fonctions.

Durant le premier remplissage, la vitesse de montée du plan d'eau est limitée en agissant, au besoin, sur les organes d'évacuation qui doivent être dimensionnés, dans toute la mesure du possible, afin de rester maître du plan d'eau. Il est conseillé de prévoir des paliers pour l'exécution de mesures à cote du plan d'eau constante et, si possible, une vidange totale ou partielle de la retenue, peu de temps après le premier remplissage, afin de comparer des mesures faites à charge d'eau identique.

7.1.2 Analyse et interprétation des résultats des mesures

7.1.2.1 Dans un premier stade,les valeurs des paramètres mesurés seront reportées, au fur et à mesure des opérations, sur des graphiques :

- en fonction du temps,

- en fonction de la montée des bétons ou des remblais,

- en fonction du niveau de la retenue.

De tels graphiques peuvent mettre en évidence des discontinuités, des évolutions anormales des grandeurs mesurées, ce qui constitue un signal d'alerte, a fortiori si le phénomène a tendance à s'accélérer.

La figure 7 donne un exemple de graphique des déformations unitaires du béton en un point de la voûte mince de Tolla (hauteur : 90 m, taux de travail moyen : 80 bars), en fonction de la montée du plan d'eau. Ce graphique montre une première discontinuité des allongements de l'extensomètre à la cote du plan d'eau 520 (signe prémonitoire d'un désordre), une accélération du phénomène à la cote 540 (détection d'une fissure dans le béton et dont le tracé, par chance, recoupait la zone d'influence du capteur qui a une base de mesure de l'ordre de 0,20 m). Cette fissuration de la voûte a conduit à la conforter par épaississement à l'aval.

7.1.2.2 Dans un deuxième stade, après obtention d'un nombre suffisant de mesures couvrant en général les périodes de première mise en eau et de première vidange, une analyse fine des résultats est entreprise.

Cette analyse statistique a pour but de séparer, pour chaque paramètre mesuré, la part à affecter aux divers effets dont il est la manifestation.

Particular care is necessary during first filling, since this is the proving period. The rate of rise of water should be controlled by the outlet works as necessary, and these works should be designed with this in mind. Pauses during filling are suggested to obtain readings with constant water level and, if possible, a complete or partial emptying of the reservoir should be arranged shortly after the filling to compare results with the same water levels.

7.1.2 Analysis and interpretation

7.1.2.1 At first, the parametric values are plotted against :

- time,
- concrete or fill level,
- reservoir level.

Such graphs show up discontinuities or abnormal bahaviour and can serve as warnings, especially if the phenomena accelerate.

Figure 7 gives an example of plotted values of concrete strain against reservoir level, at one point in the Tolla thin arch dam (90 m high, working stress 80 bars). This shows the first discontinuity with the reservoir at el. 520 (a warning) and an acceleration at el. 540 (at which level a crack in the concrete was found which by chance crossed the instrument site which extended over a length of about 0.2 m). This cracking led to remedial works consisting of thickening of the arch at the downstream face.

7.1.2.2 Subsequently, a detailed analysis is undertaken, usually after first filling and first drawdown. This statistical analysis is to determine the response of each parameter to each cause to which it reacts.

C'est ainsi que pour un barrage en béton seront distingués :

- les effets réversibles de caractère élastique, dus aux variations de la charge d'eau et de la température,

- les effets irréversibles (retrait - gonflement, fluage du béton, déformations de la fondation) qui sont de règle sur les ouvrages neufs, accompagnés parfois de fissuration, d'évolution des débits de fuite.

Cela revient, en considérant les trois variables : charge d'eau, température et temps, à établir les lois hydrostatiques et thermiques des variations réversibles des grandeurs mesurées et, partant de là, à déduire les effets irréversibles (en fonction du temps) qui sont les plus significatifs du comportement de l'ouvrage et qui parfois traduisent des phénomènes accidentels, des évolutions anormales.

Ces graphiques en fonction du temps, donnant l'évolution des paramètres de comportement de l'ouvrage "à cote du plan d'eau et température constantes", constituent donc des graphiques de surveillance.

Mais il faut signaler, à ce propos, qu'une telle analyse présente d'autant plus de difficultés que le nombre de mesures est peu élevé, que la période considérée est courte et correspond à une faible diversité de situations hydrostatiques et thermiques.

La figure 8 donne un exemple de résultats d'une analyse statistique ayant porté sur les mesures topographiques d'auscultation du barrage-voûte EDF de LAOUZAS au cours de sa mise en service (1965-1966). Il s'agit d'une voûte de 51 m de hauteur et de 290 m de longueur en crête.

Les graphiques présentés concernent le repère topographique de clé, en crête :

a) L'établissement de la loi thermique des déplacements réversibles - graphique A - a été grandement facilité par la stabilité du plan d'eau au cours de l'année 1966. Le paramètre thermique adopté est la température du béton.

b) La loi hydrostatique des déplacements réversibles du repère - graphique B - a été établie pour la baisse et la deuxième montée du plan d'eau de novembre-décembre 1965, la loi thermique intervenant pour corriger les déplacements de l'effet thermique.

c) A partir de ces deux lois, les déplacements du repère, depuis le début du remplissage, ont été corrigés des effets hydrostatiques et thermiques, et reportés en fonction du temps - graphique C, qui est un "graphique de surveillance à cote du plan d'eau et température constantes" -. Si après corrections les points restent dans la bande horizontale de dispersion, le comportement est normal ; sinon, il y a anomalie.

La même analyse a été appliquée aux mesures au fil de fondation, situé au pied amont de la console de clé (Fig.9).

Ces analyses ont décelé un mouvement irréversible de la voûte résultant :

- d'une part, d'une déformation irréversible du rocher de fondation (desserrage du rocher), qui s'est manifestée essentiellement en octobre-décembre 1965 ;

- d'autre part, d'une déformation irréversible de la voûte proprement dite, due au retrait du béton, déformation qui s'est prolongée dans le temps.

So for a concrete dam one is able to distinguish:

- the reversible, elastic effects of changes in water level and temperature,

- the irreversible results of concrete shrinkage, swelling and creep, and foundation deformation, which are inevitable in new structures and are sometimes accompanied by cracking and leakage.

This is done by considering the three variables : water load, temperature and time, and determining the reversible hydrostatic and thermal ralationship. From there, the irreversible (time dependent) effects are deduced. The latter are the most significant of the dam's behaviour and may reveal incidental effects or abnormal trends.

The resulting time plots, independent of water load and temperature, are fundamental to dam monitoring.

Such an analysis is made difficult if there are too few measurements or too short a study period with insufficient ranges of load and temperature conditions.

Figure 8 is an example of the results of statistical analysis of survey readings for EDF's Laouzas dam (51 m high, 290 m long) during its commissioning in 1965-66. The graphs in this figure plot displacements of the crown cantilever crest survey target :

a) Graph A shows the reversible displacement temperature relationship. This was greatly helped by the small changes in the reservoir level in 1966 after first filling. The temperature variable is concrete temperature.

b) In graph B, the relationship with water level is determined for the lowering and second rise in water level in November, December 1965. The temperature relationship was used to correct for thermal effects.

c) Using these two relationships, the time related movements are plotted in graph C, after correcting for water level and temperature effects.
The graph C is called "surveillance graph" : if, after correction for hydrostatic and thermal effects, all the measures are situated in the horizontal dispersion band, the behaviour of the dam is normal ; if not, there is an anomaly.

The same analysis was carried out for the foundation wire (Fig. 9).

These analyses detected an irreversible movement of the dam as a result of :

- permanent rock deformation (loosening), mainly during October-December 1965,

- permanent deformation of the arch itself due to concrete shrinkage. This deformation was less than the other but took longer.

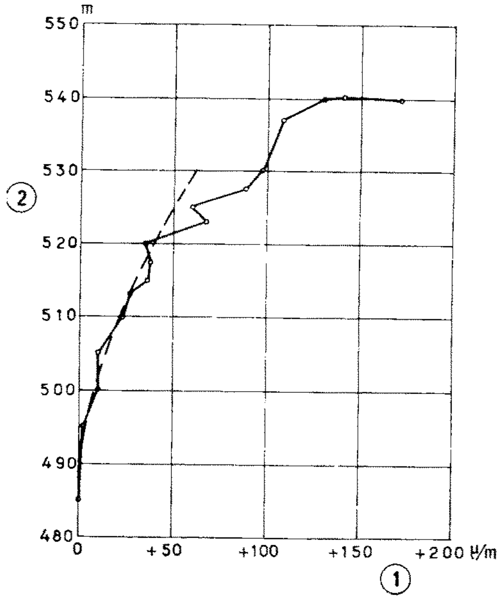


Fig. 7

Barrage-voûte de Tolla - auscultation extensométrique du béton.
Tolla arch dam. Strainmeter measurements in concrete.

(1) Allongements mesurés par l'extensomètre (en μ/m).	*(1) Measured strain (μ/m).*
(2) Cotes du plan d'eau en mètres.	*(2) Reservoir level (m).*

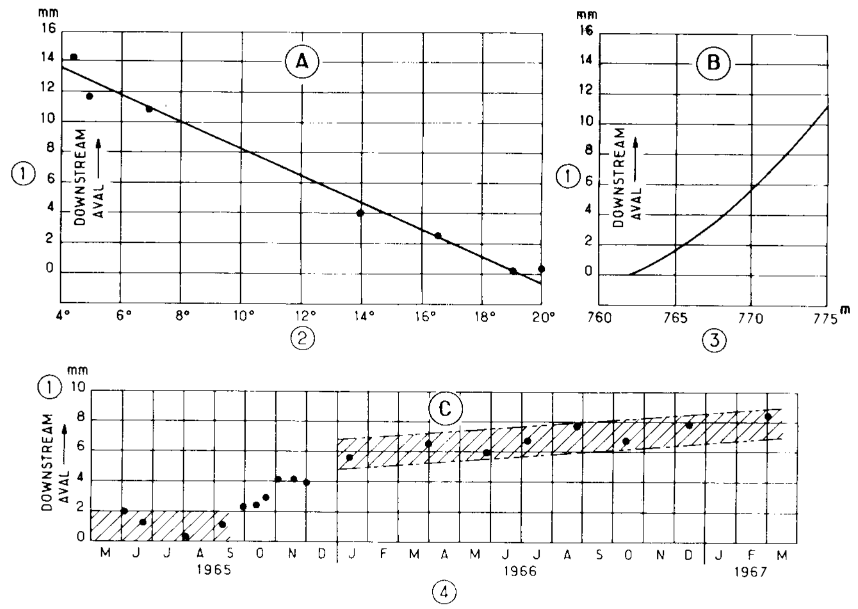


Fig. 8

Barrage de Laouzas. Repère topographique 15.

(A) Loi thermique.
(B) Loi hydrostatique.
(C) Déplacements irréversibles vers l'aval, en mm.
(1) Déplacements en mm.
(2) Températures du béton.
(3) Cotes du plan d'eau en m.
(4) Période considérée (mois et années).

Laouzas dam. Topographical target 15.

(A) Thermal law.
(B) Hydrostatic law.
(C) Irreversible displacements towards downstream, in mm.
(1) Displacements in mm.
(2) Temperatures of concrete.
(3) Water levels in m.
(4) Period taken into consideration (months and years).

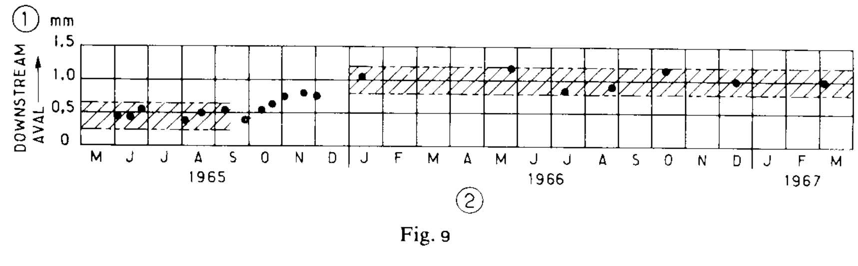


Fig. 9

Barrage de Laouzas. Fil de fondation (longueur 12 m).

(1) Déplacement irréversible vers l'aval, en mm.
(2) Période considérée (mois et années).

Laouzas dam. Foundation wire (length 12 m).

(1) Irreversible displacements towards downstream, in mm.
(2) Period under consideration (months and years).

7.1.2.3 Une autre méthode consiste à comparer les valeurs de certains paramètres mesurés avec les valeurs calculées dans le projet du barrage.

Mais, il faut remarquer à ce sujet qu'il est souvent difficile de définir le comportement d'un barrage, et surtout de sa fondation, par les valeurs absolues des paramètres mesurés, alors que les variations de ces paramètres permettent de connaître l'évolution du comportement de l'ouvrage.

Cependant, la comparaison modèle-ouvrage réel peut maintenant être mise en pratique par suite des progrès accomplis, au cours de ces dernières années, dans les méthodes de calcul des barrages (en particulier, méthode des éléments finis).

Nous donnerons comme exemple l'étude faite sur le barrage en remblai de Grand'Maison (voir chapitre 4.2.5).

Grâce au développement continu des moyens de calcul, le dimensionnement a priori des barrages en remblai se fait actuellement avec des lois de comportement des sols de plus en plus complexes (lois non linéaires, comportement élasto-plastique).

Cependant, les matériaux utilisés dans les barrages en remblai peuvent être très divers, avec chacun leur comportement propre ; il en est de même des assises du barrage. La présence de l'eau ne peut que compliquer le comportement mécanique des sols.

C'est dire la complexité des phénomènes régissant les déformations d'un barrage en remblai et la difficulté à en simuler le comportement par des modèles mathématiques.

Cette difficulté tient en grande partie à la détermination des paramètres des lois de comportement à partir d'essais de laboratoire (essais triaxiaux, essais oedométriques...).

Les mesures in situ lors de la construction du barrage ou lors de son exploitation peuvent alors servir à recaler ces paramètres et, par ajustements successifs, permettre un calcul complet, conforme aux observations.

Grâce à une telle analyse, effectuée en cours de construction, on pourra ainsi mieux prédire le comportement pour les étapes ultérieures (construction, exploitation).

La méthode de calcul par éléments finis a été appliquée à la digue de Grand'Maison, en conditions drainées, après consolidation : dans le cas particulier de ce barrage construit en quatre campagnes saisonnières de 5 mois, avec des recharges en matériaux drainants et un noyau en terres caillouteuses, la consolidation est presque immédiate ou acquise dans l'inter-saison pour le noyau.

La figure 10 donne les résultats du calcul, à deux dimensions, des déplacements internes du remblai, dans la section transversale la plus haute, pendant la construction.

7.1.2.3 In another approach, readings are compared with values calculated during the design. It must be said, in this respect, that it is often difficult to describe the behaviour of a dam, and particularly its foundation, using absolute values of measured parameters, when it is variations in these paramaters that show the behaviour of the dam.

Comparison between model and structure can, however, be made now with modern analytical methods, especially the finite element type. Grand'Maison embankment dam (see 4.2.5) will serve as an example.

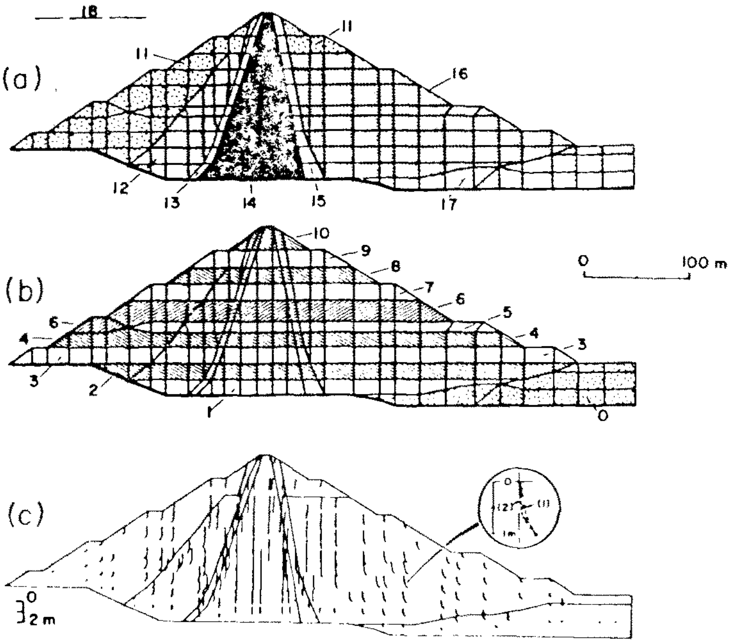
Fill dams are designed nowadays with increasingly complex constitutive equations modelling soil behaviour, including non-linear and elastic-plastic types. In addition, the materials are extremely variable, each with its own specific behaviour, as are foundations. Water further complicates the issue. The factors affecting the deformation response of embankment dams are thus extremely complex and it is difficult to simulate it by mathematical modelling.

Much of the difficulty arises from the problem of establishing constitutive equations on the basis of triaxial, oedometer and other laboratory tests.

In situ measurements during and/or after construction can be used to recalibrate the model and make it react in the same way as the dam. Such back-analysis is better able to predict behaviour for future stages of construction and operation.

For Grand'Maison dam the finite element analysis used elasto-plastic relationships in drained conditions after consolidation. This was possible because the dam was built in 4 seasons of 5 months each. The shoulders were of free draining material and the stony fill in the core consolidated almost immediately, or anyway during the non-working periods.

Figure 10 shows the results of the two-dimensional finite element displacement analysis for the highest cross section of the dam during construction.



7.2 Période d'exploitation normale

En période d'exploitation normale du barrage, le traitement des informations fournies par les mesures a pour but essentiel de mettre en évidence les évolutions éventuelles de l'ouvrage dans le temps, en séparant les phénomènes réversibles, liés aux variations de la cote de retenue et de l'état thermique de l'ouvrage, des phénomènes irréversibles ou évolutifs.

Au bout d'un certain nombre d'années d'exploitation, on dispose d'un échantillon important d'une grande diversité de cote du plan d'eau et d'état thermique du barrage, permettant une analyse statistique.

Ces analyses portant sur un grand nombre de barrages ont montré que, pour les ouvrages en béton , l'effet thermique réversible pouvait être assimilé à un effet saisonnier conduisant ainsi à s'affranchir de toute mesure de température (ce qui, par contre, est rarement possible pour un barrage mince, lors de la première mise en eau).

L'utilisation de l'ordinateur a permis d'élaborer des "modèles de comportement" dont la simplicité et l'universalité ont été largement utilisées pour standardiser le traitement, tout en facilitant l'entrée des données et en créant des restitutions de lecture aisée.

Fig 10 - Digue en remblai de GRAND'MAISON
GRAND'MAISON Embankment Dam

COUPE AMONT-AVAL LA PLUS HAUTE	HIGHEST CROSS SECTION
(a) Matériaux constituant le barrage et maillage	(a) Materials of the dam and mesh
11 Enrochement	11 Rockfill
12 Eboulis de la recharge amont	12 Upstream shell talus
13 Filtre amont	13 Upstream filter
14 Noyau	14 Core
15 Filtre et drain aval	15 Downstream filter and drain
16 Eboulis de la recharge aval	16 Downstream shell talus
17 Alluvions, éboulis, moraines en place	17 Alluvium, talus, moraine in place
18 Retenue	18 Reservoir level
(b) Successions des couches de calculs modélisées	(b) Stages in analysis
0 Terrain	0 Ground in place
1 Première couche du calcul	1 1st layer
10 Dixième couche du calcul	10 10th layer
(c) Histoire des déplacements	(c) Displacements during construction
1 Déplacements calculés	1 Calculated displacements
2 Déplacements mesurés	2 Measured displacements

7.2 Normal operation

During operation, the main object of monitoring is to record the behaviour of the dam with time, separating the reversible temperature and load effects from the irreversible. After a number of years, with the large quantity of data available, a further statistical analysis can be done. Such analyses which have been carried out for a large number of dams have shown that for concrete dams the reversible thermal effect is seasonal and no further temperature measurements are necessary (although they are still important for a thin arch dam during first filling).

The computer has made it possible to develop "performance models" whose simplicity and universal application have been used to standardize the procedure ; data input and output is simple. The method consists of fitting an equation to the result using the following variables :

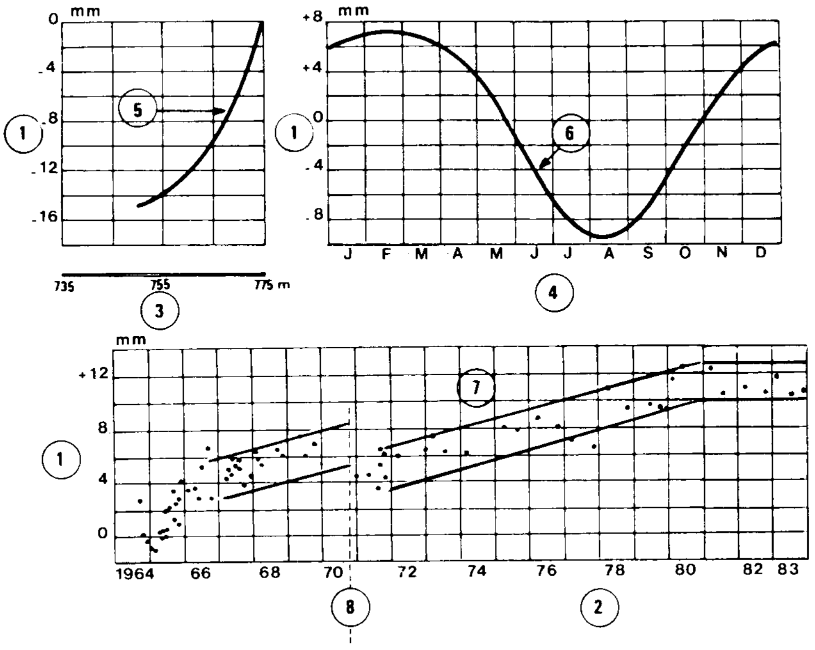


Fig. 11

Barrage-voûte de Laouzas — Déplacements amont-aval du repère topographique de clé, à proximité de la crête

Laouzas arch dam — Upstream-downstream displacements of the survey point situated on the crown cantilever, near the crest

1. Déplacements en mm : + vers l'aval	*1. Displacements (mm) : + downstreamwards*
2. Années	*2. Years*
3. Niveau de la retenue	*3. Réservoir level (m)*
4. Mois	*4. Months*
5. Loi hydrostatique	*5. Hydrostatic law*
6. Loi thermique saisonnière	*6. Thermal (seasonal) law*
7. Déplacements irréversibles vers l'aval	*7. Irreversible displacements*
8. Reclavage de la voûte	*8. Arch joints regrouted*

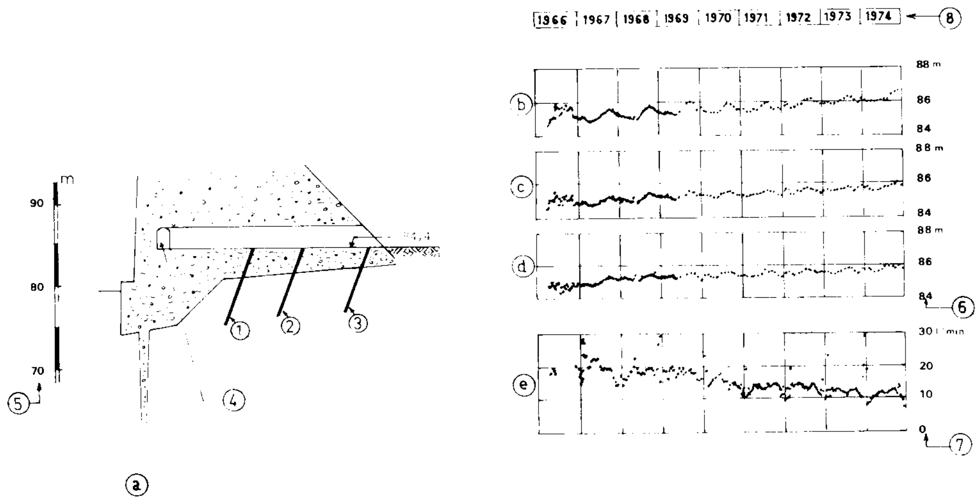


Fig. 12

Barrage de Guerlédan.
Efficacité du drainage de la fondation des plots 1 et 2.
Guerledan dam. Efficiency of foundation drainage below blocks 1 and 2.

(a)	Coupe du plot 2.	(*a*)	*Section through block 2.*
(b) (c) (d)	Graphiques des niveaux piézométriques aux piézomètres 1, 2, 3 (à conditions constantes reconstituées de cote amont : retenue normale et de saison : saison moyenne).	(*b*) (*c*) (*d*)	*Piezometric levels from piezometers 1, 2 and 3, corrected for normal reservoir level and average weather.*
(e)	Graphique des débits collectés par des drains de fondation dans la zone des plots 1 et 2 (à conditions constantes reconstituées de cote amont et de saison).	(*e*)	*Foundation drain discharge near blocks 1 and 2, corrected for normal reservoir and average weather.*
(1) (2) (3)	Piézomètres.	(*1*) (*2*) (*3*)	*Piezometers.*
(4)	Galerie de visite et drainage.	(*4*)	*Inspection and drainage gallery.*
(5)	Altitudes du barrage (en mètres).	(*5*)	*Dam altitudes (m).*
(6)	Altitudes des niveaux piézométriques (en mètres).	(*6*)	*Piezometric levels (m).*
(7)	Débits de fuites (en l/mn).	(*7*)	*Leakage (l/mn).*
(8)	Années.	(*8*)	*Year.*

La méthode consiste à ajuster une loi sur les résultats des mesures, en faisant intervenir les variables :

- la charge hydrostatique z, sous la forme d'une expression :

$a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4$

- la date de la mesure dans l'année : s ou paramètre saisonnier, sous la forme d'une expression :

$a_5 \cos(s) + a_6 \sin(s) + a_7 \sin^2(s) + a_8 \sin(s) \cos(s)$

- le temps t compté à partir de l'opération origine, sous la forme de deux expressions :

évolution acyclique amortie : $a_9 e^{-t}$

évolution acyclique accélerée : $a_{10} e^{t}$

Le graphique des résultats des mesures en fonction du temps - phénomènes irréversibles - constitue en particulier un "graphique de surveillance à conditions hydrostatiques et saisonnières constantes".

Cette méthode est applicable à toutes les grandeurs mesurées sur les barrages. Mais il faut reconnaître que les modèles mathématiques donnent principalement des résultats satisfaisants pour les mesures de déplacements, de déformations internes ; des résultats peuvent être moins bons pour les mesures piézométriques, les mesures de débits de fuites, plus spécialement quand la pluviométrie intervient.

Exemple : Le barrage-voûte du LAOUZAS (Fig.11)

La figure 11 donne les résultats de l'application de la méthode aux déplacements du repère topographique de clé, en crête, même repère que celui étudié au chapitre 7.1.2.2. ci-dessus (Fig.8).

Ici, le paramètre thermique est différent : la saison, au lieu de la température du béton adoptée précédemment lors de la mise en eau.

Le graphique des déplacements irréversibles (en fonction du temps) présente les mêmes résultats, pour la période de mise en service de l'ouvrage, que celui de la Fig. 8 (on constate cependant un peu plus de dispersion sur la Fig.11).

Au cours des années ayant suivi la mise en service (période 1966-1980), le mouvement, dû essentiellement au retrait du béton, s'est poursuivi vers l'aval : de l'ordre de 0,75 mm par an.

Un reclavage de la voûte, en 1970, a repoussé le barrage vers l'amont, mais n'a pas pour autant arrêté le mouvement irréversible vers l'aval.

Une stabilisation du mouvement se manifeste depuis 1980.

- for hydrostatic load, z :

$a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4$

- date of the measurement within the year, s, for the thermal effect :

$a_5 \cos(s) + a_6 \cos(s) + a_7 \sin^2(s) + a_8 \sin(s) \cos(s)$

- time, t, measured from original measurement, in two expressions :

$a_9 e^{-t}$ for the non-cyclic damped effect ;

$a_{10} e^t$ for the non-cyclic accelerated effect.

The time plots (irreversible effects) are independant of water level and seasonal influences.

The method can be applied to all parameters. However, it must be realised that mathematical models work well mainly for displacements and internal deformations. The results are less good for water pressures and seepage flows, especially when rain must be taken into account.

Example : Laouzas arch dam (Fig. 11)

This method was applied to the movements of the crown cantilever survey target described in 7.1.2.2 during first filling (Fig. 8). This time, the season rather than the concrete temperature was used as the temperature variable.

The time plot of irreversible displacements is the same as this in figure 8, and refers to the commissioning period (there is rather more scatter in figure 11).

After commissioning, during the period 1966-1980 the movement, mainly due to concrete shrinkage, continued at about 0.75 mm per year.

The regrouting of the arch joints, in 1970, caused an upstream displacement but did not stop the ongoing downstream movement. It appears to have stopped in 1980.

Exemple : Le barrage-poids de GUERLEDAN (Fig.12)

Le barrage-poids de GUERLEDAN est un ouvrage en béton, de 55 m de hauteur.

La méthode d'analyse précitée a été appliquée aux mesures piézométriques et de débits dans la fondation . Les pressions dans la fondation sont limitées par des drains forés, à l'aval du rideau d'injection, depuis la galerie de pied et surveillées par des piézomètres.

Les graphiques des résultats de l'analyse ont mis en évidence une lente montée du niveau piézométrique en plusieurs points sous le plot, accompagnée d'une diminution du débit collecté dans cette zone. Des mesures de rénovation du drainage ont pu être prises avant l'apparition de tout désordre.

CONCLUSION

Les considérations qui précèdent montrent que le contrôle de la sécurité des barrages est l'objectif primordial de l'auscultation.

On peut dire qu'ausculter un barrage c'est mettre le maximum de chances de son côté afin que puissent être prises les mesures préventives destinées à éviter la catastrophe, ce qui suffit à justifier tous les efforts faits dans ce sens.

Il apparaît d'ailleurs que, dans bien des cas, les barrages accidentés ne paraissent pas avoir fait l'objet de mesures de surveillance soignées.

Pour qu'une auscultation soit efficace, il est nécessaire :

- de disposer d'appareils de mesures de très bonne qualité, présentant une grande fiabilité,

- d'assurer une parfaite organisation des mesures,

- de mettre en oeuvre des méthodes d'analyse et d'interprétation rapides des mesures,

- de procéder périodiquement à des surveillances visuelles des barrages et de leurs abords.

Il faut également souligner le rôle important joué par les hommes responsables de la surveillance des barrages et chargés d'interpréter les résultats de l'analyse des mesures. La sécurité des barrages repose pour une large part sur ce jugement qui, lui même, s'appuie sur l'expérience, sur des comparaisons avec d'autres ouvrages.

Example : Guerledan gravity dam (Fig. 12)

The analysis method described above was used for this 55 m high gravity dam for foundation pressures and seepages. Foundation pressures are controlled by drains bored from the gallery downstream of the grout curtain and are monitored by piezometers.

The plotted results showed a slow rise in piezometric level at several points under the dam block, combined with a reduction in seepage.

As a result, the drains were refurbished before anything serious occurred.

CONCLUSION

Monitoring is primarily a means of checking dam safety and, so to speak, of taking out an insurance against accidents by allowing remedial action to be taken in good time to prevent disaster. This alone is ample justification of the time and effort involved.

It is striking that many recorded dam accidents have occurred to structures not provided with adequate monitoring systems or procedures.

Effective monitoring means :

- sound, reliable instruments,
- strict procedures for instrumental data collection,
- swift data analysis and interpretation methods,
- periodical visual inspection of the dam and site.

The men responsible for dam inspection, monitoring and data interpretation are vitally important. Dam safety ultimately depends on their engineering judgement, and their experience of other dams for comparision.

Appendix E
Annexe E

REPORT BY THE ITALIAN NATIONAL COMMITTEE

What described in this report represents the state of the art for the monitoring of existing dams in Italy.

Obviously this state is consistent with geological, morphological, seismic and socio-political situation of Italian reality.

This situation can be summarized as follows: Italy, as it's well known, is a densely populated country, highly seismic and particularly rich in endowments of nature and artistic monuments which must be carefully guarded (and the reservoir construction sometimes impacts heavily on the environment).

From the climatic point of view, big seasonal variations - both thermal and meteorological - are present in Italy; the altitude influence of reservoirs (from room to 2500 m asl) is very important.

As regards to geologic characterized of Italian reservoirs. using perhaps a too curt scheme, the territory can be subdivided into two zones:

- The Alps circle: characteristics for the most part by gneiss and schists, much more rarely by granites and limestones.

- The Apennines region, in which on the contrary there is a marked prevalence of limestones, arenaceous pelitic formations, clays and clay-shales; metamorphic rocks are found in the southern part.

As concerns the big islands, the Sicilian reservoirs are located in limestones and metamorphic rocks; the Sardinian ones mainly in granites.

The lithologic diversity of the territory and the different mechanical features of the foundation rocks had a bearing on the different types and geometric characteristics of Italian dams.

Thus, of the 408 big Italian dams (as listed in the "World Register of Dams" of ICOLD, 1984), 95 are arch concrete dams, 198 massive-gravity concrete dams, 24 buttress concrete dams, 10 multiple-arch concrete dams, 25 rockfill dams and 56 earth dams.

We can add - as a sketchy historical background - that 199 dams were built before 1950; 204 were built between 1951 and 1977.

A natural consequence of these data is - as evidenced in the following Sections of our Report - the interest of our technicians for the aging problems of dams, and hence for their monitoring in view of a satisfactory characterization of their present state.

1. THE CONDITIONS FOR DAM SAFETY

In view of the fact, that dams have a high potential for catastrophic descruction of human life and property, there exists the necessity for continuous monitoring of their behaviour. This necessity is universally recognized and accepted by all countries.

Great progress has been achieved recently in instrumentation, data trasmission and processing systems in terms of reliability, precision, speed and accuracy of measurement acquisition. Also, in the recording, comparing, evaluating and transferring of these measurements over long distances, there has been great progress. For this reason it is necessary to re-examine the methods currently used for dam surveillance and the entire approach to dam safety, in order to fully exploit the technological progress available for reducing the risk presented by dams already in operation, or to be built in the future.

The concepts of risk and, in a complementary way, of safety, may be defined in different ways and consequently, have different implications on the economic as well as on the social plane. A precise and analytic definition is not strictly necessary for establishing correct control criteria of dams and barrages. The control system has to ascertain that the dam behaviour coincides with the design forecasts, both in the constructional phase and operational phase.

As long as this coincidence exists, the structure offers the degree of safety that has been defined by the designer and approved by supervising authorities at the time of design. If at any time during construction or operation, there is a significant departure from the behaviour design forecast, it becomes the task of the control system to show the phenomenon and correlate it with all the quantities that may have a bearing on the behaviour of the dam. In this event, the dam will have to be checked out anew in overall terms and possibly redesigned.

The most suitable time for establishing the degree of safety and risk for the dam, is during the design stage. In order for the control to carry out its task without recourse to a subjective analysis of the in-service dam safety, it is necessary that the reference "model" be defined at the design stage, establishing quantities to be kept under observation, and their field of variations. The control quantities will include not only those directly connected with the structure and project, but also those that define the environmental and operational conditions.

For structures already existing, whose designs have not adhered to the criteria above, operational control is unable to refer to a model defined at the design stage.

While it is certainly possible and advisable to check or re-design these structures a criterion of "a posteriori" control is applicable nevertheless, this being based on analyses of the observations on the behaviour of the structure and their overall evaluation in statistical terms.

1.1 Control Criteria

Two fundamental criteria (alternative or complementary) have thus been identified for the control of dam behaviour, applicable to structures being designed, as well as those already existing and in operation.

The first control criteria is the comparison of the dam behaviour with the analytical "model" forecasts, defined by the design. The comparison is carried out via analysis of a set of physical quantities describing the structures effective behaviour. The forecast values and the permissible departures relating to the corresponding operational conditions are obtained from the model. Hence it is necessary to measure the quantities that best characterize the structures behavior, and those which describe the external conditions; these last are needed to be introduced in the reference model, so as to derive the terms of comparison with the observations.

The second criteria is the statistical comparison of a set of significant measurements with the corresponding values obtained throught the life of the structure. In other words, one needs to verify that the variables identifying the behaviour of the structure, as well as those related to the environmental and operational conditions, are within the range of values previously obtained and are mutually consistent. On the conceptual and applicative planes, this control criterion can substantially approach the preceding one, if the set of quantities obtained, is large enough - and sufficiently extended in time - to reconstruct an empirical model of the dam behavior.

The weight and efficiency of the statistical criterion increase with the life of the structure; it makes possible to verify the design model and the parameters defining it.

The control criteria, mentioned above, are at the present time applicable and actually valid. In Italy they represent a rational objective tool for evaluating the safety of dams; its use is recommended for any type of structure.

1.2 Analysis of Risk

Before defining the reference model to be used for safety checks, it is important to identify the risk factors that can cause a crisis in the structure or at least compromise it operationally.

It should be taken into account that while some of the risk factors are inherent in the structure, (understood as being a single element together with its foundation) others are entirely independent of it, and caused by outside physical events connected with the natural environment in which it is placed.

Among these latter, the following may be considered typical of an ambient situation such as the Italian one:

- seismic events
- hydrological and metereological events with exceptional features
- ground dislocations in main upstream reservoir or around it, originating independently and not as a consequence of the other events sited.

For what concerns the inherent risk factors, it is to be observed that generally these show up with "irregularities" in the behavior of the dam or its foundations, as compared with the reference model; for instance:

- irregularities that jeopardize the integrity of the structure itself and reflect adversely on its static and/or hydraulic functionality;
- widespread degradation of the resistence characteristics of the

materials making up the dam and the foundation ground;
- irregularities in the deformation behaviour of the dam or of the foundation ground;
- irregularities in the amount and distribution of the uplift pressures or of the interstitial pressures.

The risk factors listed above are potentially present in every structure, but at times some of these may take on a prominent profile.

It is the task of the designer, or at any rate of those responsible for setting up the "reference model", to identify the specific risk factors of the structure and proceed to an evaluation of the "degree -or probability- of risk" to which the structure itself is exposed in a given moment of its life.

It is understood that this degree of risk depends both on the ambient conditions as well as on the type, size, destination and age of the dam, as well as the sizing and reliability of its outlet facilities.

1.3 Requisites of the Control System

Regardless of the criteria observed, the structure of the control system, and the methods of obtaining and processing the data should meet certain prerequisites. Moreover, they should be functional and rational; this can be achieved as a consequence of the developments in the field of measurement equipment and the means of transmission and treatment of information.

- The preliminary prerequisite of the control system, is the consistency between the speed and frequency of the observations and the rate of evolution of the phenomena to be observed. In this context, replacing manual procedures of data acquisition with automatic ones and the mechanical and graphic recording systems with electronic, numerical ones, makes possible to follow the evolution of highly rapid phenomena (i.e. seismic phenomena) and their effects.

- Another essential feature of the control system is the possibility to take into simultaneous and overall account all the processes of analysis and comparison of the observations. Indeed, the check should be based on all the quantities obtained - whose compatibility may be ascertained beforehand - and not on individual variables or groups.

- A further feature, that can be currently realized, is the containment within minimum values (almost nil) of the time interval between the execution of the measurement and the completion of the processing and analysing procedures.

The activation of the automatic control system according to the above specified criteria makes possible to conclude the control procedure within a negligible time interval, thereby almost eliminating one of the most adverse inherent limitations of control procedures based on observation of the real behaviour and their subsequent analysis.

2. PHYSICAL QUANTITIES TO BE CHECKED

As mentioned before, the dam is subjected -during its service life- to variations in its surrounding environment, to which it responds according to its properties.

Therefore, in observing the behaviour of a dam, the individual quantities obtained depend on:

- cause or ambient quantities (with which their variations induce changes in the structure);
- effect quantities (which constitute the response of the structure to the variations of the cause quantities).

The main cause quantities, acting on the structure are:

- reservoir level;
- air, water and concrete temperature;
- precipitations (rainfall and snow);
- atmospheric conditions (humidity, pressure, wind);
- thickness of the ice;
- bathymetry of the basin;
- seismic events;
- flood discharge;
- independent movements of the foundation and the banks.

The main effect quantities are:

- internal strains and stresses;
- local stresses;
- horizontal and vertical displacements (absolute and relative);
- rotations;
- movement of joints and cracks;
- seepage discharges and their turbidity;
- uplift pressures and interstitial pressures;
- modifications in the physical-mechanical characteristics of the materials.

The cause, and effect quantities undergo continuous variations with time. These variations have to be measured for evaluating the reciprocal correlations that are associated with the structure's mode of response. Since these measurements are to be systematically repeated a great number of times during the life of the structure, the only practical solution is to provide for permanent measurement installations, specifically destined for surveillance.

3. MEASUREMENT SYSTEMS

A measurement system for the static or seismic control of a dam and its foundation is a co-ordinated entity made up of a number of instruments and equipmentment to obtain the physical quantities and to transform and process the information acquired. A measurement system calls for a single time and space reference and is subordinate to the type of dam and the period of the dam life.

The practical definition of a measurement system for a given dam-foundation entity involves the analysis and definition of the following points:

- the elements that condition the safety of the dam-foundation entity;
- the quantities that, for each element taken into consideration, show its behaviour in terms of safety;
- the instruments to be employed for the measurement of the chosen quantities, the manner of installation, the precision and reliability of the measurements;
- the density and the distribution of the instruments inside and outside

the dam-foundation entity;
- the frequency of the observations.

For concrete dams, the essential elements of safety, in greater or lesser measure in relation to the different tipologies, are:

- the foundation rock;
- the foundation rock/dam contact surface;
- the dam structure;
- the joints.

For embankment dams, the observation is to be extended to the dam/foundation complex. The elements listed hereunder are essential in the context of the safety of the structure and are to be put under particular scruting:

- foundation ground;
- area of contact between foundation ground and dam body;
- dam body;
- water thightness structures in the foundation;
- upstream waterproof facing;
- waterproof nucleus;
- built-up masonry structures introduced in the foundation ground or in the dam body (ducts, outlet organs, etc.);
- draining and filtering elements.

3.1 Requisitions of the Measurement System

The importance of the individual structural elements of a dam and of the related measurements varies in relation to the different phases of life of the structure (construction, temporary operation and commissioning, normal operation) and to the aims of the measurements themselves (safety, outage, informative).

- During execution and commissioning, checks are made for immediate safety by showing the overall actual behaviour of the dam-foundation entity determined by complex factors that are not always familiar during the design phase. They represent the initial verification of the design and facilitate (if so needeed) in carrying out modifications during the construction of both the design itself as also of the manner of realization.

- During operation, the checks provide information on the structure behaviour as a whole, and also for points of special interest, evidencing any evolution over a period of time.
  It is advisable to provide certain measurements for research aimed at resolving specific techno-scientific problems that often transcend the limits of the structure under consideration.

In setting up a measurement system, it is advisable to take into account the concepts and requirements listed hereunder:

- a measurement system should be designed and installed by specialized personnel;
- the environmental difficulties (climatic, geological and seismic) that are often present entail consequences for the type of instrumentation, the number and the frequency of the readings;
- it is advisable not to limit the initial installations and readings, since it is possible to make subsequent reductions when the essential parameters to be kept under check have been identified; in this

context the fact should also be taken into account that the embedded or incorporated instruments often cannot be replaced or may have a short life-span;
- whenever possible, it is advisable to set up installations that make it possible to acquire the same quantity with several instruments, so as to facilitate confirmations and checks;
- in the case of automation and transmission of the measurements, it is advisable to have at hand the alternative of being able to carry out measurements manually on site;
- there being a general preference for "quickly obtained" measurements, the systematic use of geodetic measurements is currently limited to "single cases";
- a systematic visual inspection should always be provided for, by way of integration of the information of any measurement system whatsoever.

It is advisable that the measurement system be articulated on several levels of completeness and further investigation:

- a level of maximum detail, to be reserved for the most significant cross-sections for which the greatest amount of information is to be acquired;
- one or more levels of lesser detail for the other cross-sections, capable of offering a knowledge of the overall behaviour of the structure via comparison with the information provided by the cross-sections deploying a higher number of instruments.

3.2 The Definition and Setting up of the Measurement System

The defining and setting up of a measurement system depends on the type of dam, its period of life, its dimensions, the reservoir capacity and the human risk factor connected with the population density downstream of the structure.

Only some of the measured quantities are the same for different types of dams.

The constructional typology, the materials used, the dimensions, the age: all of these make the quantities involved for dam safety, different from case to case.

An initial sub-division may be related to the material employed:

- concrete;
- loose materials (earth or rockfill).

In the case of concrete dams, distinction may be made on the basis of type:

- arch dam;
- gravity dam;
- buttress dam.

The embankment dams may be grouped together in the following two types:

- dams with upstream waterproofing;
- dams with waterproof nucleus.

Tables 1 (a,b,c), for concrete dams, and Tables 2 (a,b) for earth dams, show the quantities to be measured, as per the list set out in

C O N C R E T E D A M S

Relevance of safety levels

** Critical situation (up to collapse)
* Out of service (total or partial)
0 Check

GR = Gravity dam
BU = Buttress dam
AR = Arch dam

Quantities to be measured: environment	Construction	Temporary operation and trial test	Operation	Instruments
Air temperature	*	0	0	Thermometers
Snow and rain fall	0	0	0	Snow and rain gauges
External pressure	0	0	0	Barometers
Humidity	0	0	0	Hygrometers
Water temperature	–	0	0	Thermometers
Water level	–	*	*	Levelling staff. hydrostatic balance
Ice thickness	–	0	0	
Batyhmetry	–	0	*	Sonic and radar sounding

Tab. 1a

Quantities to be measured:	Construction			1st operation and trial			Operation			Instruments
in the dam body	GR	BU	AR	GR	BU	AR	GR	BU	AR	
Horizontal displacements	–	–	–	**	**	**	**	**	**	Triangulations, collimations, direct and inverted plumb line
Vertical displacements	*	*	–	**	**	*	*	*	0	Topographic or hydrostatic levelling
Rotations	*	*	–	**	**	*	*	*	0	Movable or fixed clinometer
Movements of joints	0	0	0	*	*	*	0	0	0	Dilatometers, joints meters, extensom.
Movements of cracks	**	**	**	**	**	**	**	**	**	Dilatometers, joint guanges meters, extensometers, acoustic emission
Concrete temperatures	*	*	*	0	0	0	0	0	0	Thermometers
Concrete deformations	0	0	0	0	0	0	0	0	0	Extensometers
Stresses	0	0	0	0	0	0	0	0	0	Stress meters
Seepages	–	–	–	–	**	**	**	**	**	Weirs, volumetric measurements

Tab. 1b

Quantities to be measured:	Construction			1st operation and trial			Operation			Instruments
in the fondation	GR	BU	AR	GR	BU	AR	GR	BU	AR	
Horizontal displacements				**	**	**	**	**	**	Inverted plumb-lines, inclinometers
Vertical displacements	*	*	*	**	**	*	*	*	0	Topographic or hydrostatic levelling extensometers
Rock deformation	0	0	0	0	0	0	0	0	0	Extensometers
Elastic modulus	0	0	0	0	0	0				Sonic core, seismic velocity
Stresses	0	0	0	0	0	0				Stress meters
Under and pore pressions				**	**	*	*	*	0	Pressure cells, stand pipe piezometers manometric cells
Underseepages				**	**	**	**	**	**	Weirs, volumetric measurements

Tab. 1c

EARTH FILL DAMS

Relevance of safety levels

** Critical situation (up to collapse)
* Out of service (total or partial)
0 Check

UF = Upstream waterproof face
C = Impermeable core

Quantities to be measured: environment	Construction	Temporary operation and trial test	Operation	Instruments
Air temperature	0	0	0	Thermometers
Snow and rain fall	0	0	0	Snow and rain gauges
External pressure	0	0	0	Barometers
Humidity	0	0	0	Hygrometers
Water temperature	–	0	0	Thermometers
Water level	–	*	*	Levelling staff. hidrostatic balance
Ice thickness	–	0	0	
Bathymetry	–	0	*	Sonic and radar sounding

Tab. 2a

Quantities to be measured:	Construction		Temporary operation and trial test		Operation		Instruments
	UF	C	UF	C	UF	C	
Settlements	**	**	**	**	*	*	Topographic or hydrostatic levelling settlement devices
Horizontal displacements			**	**	*	*	Triangulation, collimation inverted plumb line inclinometers extensometers invar wires
Deformations	*	*	*	*	0	0	Extensometers
Total pressures	0	0	0	0	0	0	Pressure gauges
Pore pression in the dam body		**	**	**	**	**	Pressure cells
Pore pression and ground water level in the fundat.	**	**	**	**	*	*	Pressure cells and stand pipe piezometers
Seepages			**	**	**	**	Weirs, volumetric measurements
Turbidity			0	*	0	*	Turbidimeter

Tab. 2b

paragraph 2.

For each quantity an indication is provided of its importance as related to safety, outage and scientific knowledge, during the three different periods of the structure's life - construction, first reservoir filling, commissioning and operation-.

Schematic indication is also provided for the most common types of measuring instruments employed.

The definition of a "standard measurement system" is not an easy task, and needs separate definition in each single instance.

4. MEASUREMENT SYSTEM FOR SEISMIC SURVEILLANCE

Seismic measurement and surveillance installations include devices that depend on the seismic characteristics of the dam site. Such installations may be called for, even when the natural seismic levels are not high; typical instances being the case of an extended reservoir or special situations.

Seismic surveillance systems are again called for when there are shock-producing activities in the dam vicinity (quarries, mines, etc.), or for diagnostic purposes (in this case systematically repeated, artificial excitations are provided for during the operation of the structure).

Designing a seismic measurement and surveillance installation generally covers the following phases:

- choosing the number and position of the sensors to be installed;
- choosing the type of sensors in relation to both the seismologic features of the site as also the type of dam;
- choosing the type and characteristics of the data recording system (and of on-line processing, if provided for).

4.1 Choosing of the Most Suitable Measuring Instruments in Relation to the Seismologic Features of the Site and the Type of Dam

Depending on the local seismic level and on the magnitude of earthquakes capable of inducing significant effects on the safety of the structure, a decision has to be made in the first instance of the minimal threshould of events to be investigated.

Indeed, the reading of extremely weak quakes, which entails no consequence for the safety of the structure, is usually of no interest, unless it be for diagnostic purposes.

Choosing the most suitable type of sensor is to be made on the basis of:

- the maximum foreseeable amplitude of the signal. The "full scale" of the sensor must be large enough to avoid saturation, and thus loss of information, in the case of high intensity events;

- the spectral content of the quakes as a function of the frequency. Should the seismic spectrum be characterized mainly by low frequencies, it is advisable to have recourse to seisometers, that is to say, instruments that are sensitive to the velocity of the point.

If, on the other hand, the spectrum is characterized mainly by high frequencies (i.e. over 10 hz), accelerometers should then be employed. Owing to the difficulty in installation, it is not usual to use instruments that are sensitive to displacements of the point, (as it would be advisable in the case of very low frequencies, lower than about 2 Hz):

- the type of dam, and its dimensions, which influence its natural frequencies.

The frequency range of the response spectrum depends on the type of structure (in concrete or in loose materials).

For concrete dams the natural frequencies of the first modes may vary between some fractions of a Hz (in the case of large arch-gravity dams, having large mass and high flexibility) to a few tens of Hz, in the case of small, thin double-curvature dams (having small mass and considerable rigidity).

For earth or rockfill dams, the natural frequency field extends from some fraction of a Hz to a few Hz, depending on the dimensions, the type of embankment material and type of foundation.

The frequencies to consider for choosing the instruments are:

- the ground motion frequencies, for instruments to be installed in the foundation; normally used are "strong-motion" type accelerometers offering 0.01 g threshold and full-scale between 0.5 and 2 g;

- those corresponding to the response spectrum peaks of the structure, for the instruments to be installed on the dam itself.

4.2 Choosing the Significant Positions for Installation of the Sensors, in Relation to the Quantities to be Obtained and According to the Constructional Typology

Different considerations apply in deploying the seismic sensors, depending on whether the sensor is to be installed in the foundation or in the dam body.

The foundation sensors are intended to characterize the input to which the structure is subjected. The dam body sensors are intended to obtain the output, or structural response. In both cases, the most significant points are chosen, taking into account the obvious need to contain the number of sensors and the related overall cost of the installation.

In the foundation, a complete description of the input, calls for a fair number (4-5, or more) of 3-component (E-W, N-S and vertical) units, since the amplitudes and the phases of oscillation may differ even substantially from point to point.

In practice, such a number of instrument and components are found to be justified in the case of large gravity or arch-gravity dams.

For what concerns small gravity or vaulted dams, it suffices to employ two accelerometers on each of the two banks, located at about one-half the height, each having two horizontal components.

Rather than being aligned N-S and E-W, the two directions of the horizontal movement are made to correspond to directions that are more significant from the structural standpoint: for example, with the upstream-downstream directions, and the direction perpendicular to the precedent (straight from one side of the valley to the other).

In the dam body, the positions and directions of greater interest are usually those that correspond to the maximum amplifications of the ground motion. They are obtained from a dynamic analysis of the structure, carried out by numerical simulation models. Generally, these positions may coincide with the "antinodes" (locations of maximum amplitude vibrations) of the first natural modes of structural vibration.

In the case of a concrete gravity dam or an embankment dam, it is advisable to deploy instruments at specific points along the crest. The operation is limited to obtaining the upstream-downstream component, and possibly the vertical one.

For buttress dams, where the "right-left bank" response may be found to be strongly amplified and therefore dangerous, it is while worthwhile to locate a number of sensors at about one-half the height in the downstream surface of the buttress.

Besides the cinematic quantities mentioned above, there are others that may be of interest for purposes of evaluating the seismic safety of the structure. These are, for instance, dynamic unit dilations, dynamic uplift pressures or the hydrodynamic pressures of the reservoir water on the upstream face.

4.3 Choosing the Seismic Surveillance System

A Seismic surveillance system is a complex system made up of sensors and equipment for acquisition, recording and processing of the signals obtained during the seismic event.

The instrumentation for the recording of seismic phenomena may be broken down according to a number of particular features, that generally determine their field of application. The categories being:

- instrumentation with recording on paper;
- instrumentation with recording on photographic film;
- instrumentation with analog recording on magnetic tape;
- instrumentation with digital recording on magnetic tape;
- instrumentation with solid state memory recording.

The following two solutions for a seismic surveillance system of dams have been identified currently as typical solutions in the context of Italian experience.

- "Distributed" equipment with seismic phenomena recording, directly on the measuring instruments - accelerographs or seismographic recorders -;
- "Centralized" equipment, with recording of the seismic phenomena on a central acquisition unit and recording at a distance from the sensors via measurement cable connections.

The latter solution makes it possible to check in real time the excitation, and consequently the possible damage to a structure subjected to a seismic event.

5. FREQUENCY OF THE MEASUREMENTS

The validity of a control system presupposes not only the use of a representative reference model for the structure, but also the choice of adeguate frequencies for reading of the data, and the resulting correct frequency for comparison between the observed and the forecast data.

Such frequency depends on:

- the quantity to be measured;
- the variation speed of the parameters (i.e. hydrostatic load, temperatures) that have bearing on the quantities to be measured;
- the phase of life of the structure;
- the "sensitivity" of the measurement device;
- the specific requirements (special studies, particular regulations issued by the authorities, possible anomalous situations, etc.).

In other words, the frequency of observation should be consistent with the time intervals during which significant variations may occur in the relevant quantities (and be identified with the measurement devices employed).

In general terms, the following criteria have been applied in Italy:

- All the measurements should have a well defined origin reference, connected with the ambient conditions prior to the construction;
- During the first reservoir filling, the measurements should be linked to the reservoir filling program. Should, this be carried out - as usual - in stages with intervals for observations, then it's necessary to execute at least one complete series of measurements, and processing and comparison of the gathered data with the design model data during each interval.
  Also, it is advisable to effect the following operations with weekly, or daily frequency: visual examination of the dam faces and the supporting area, reading of the pendulums, leakage discharges and uplift pressures;
- During normal operation (seasonal cycle in most cases), the measurements are effected at constant time intervals, in particular:
- reading of pendulums and piezometers with fortnightly frequency;
- readings of the inclinometers, strain-gauges and uplift pressure manometers with monthly frequency;
- measurements of collimation and settlement devices, with quarterly frequency;
- levelling and geodetic measurements with half-yearly or annual frequency.

During the trial period of operation and also during normal operation, Italian regulations require daily readings of the ambient quantities. Normally, the same frequency is maintained also for the seepage losses.

It is to be noted, that checking the dam with a reasonable frequency involves a risk linked with the time interval between two successive measurements. Under normal conditions, the maximum interval between readings of the most significant quantities should not in any case exceed 15 days.

In the case of an automatic measurement system, check-ups for the structure may be carried out in real time and in a continuous manner, while the recording of the data may be limited to the daily type of frequency.

6. AUTOMATION OF THE MEASUREMENT SYSTEM

For what concerns the problem of automation of the static or seismic measurement system, today's specialist is faced with making a choice that entails decisional responsibility, (a situation that was absent only a few years ago). It is undeniable that technological developments in the field of computers make it possible to approach the problems of monitoring large structures, on the basis of automation and at an acceptable cost. However, in making this choice, the advantages and disadvantages of an automatic monitoring system must be carefully evaluated. It must be clear what help can be obtained from these new tools and what errors or misunderstandings are to be avoided.

It should be kept in mind that manual reading is entrusted to the capability and willingness of the personnel responsible. Until now many instances have shown that such personnel have not in all cases been up to the task with which they have been charged, also for reasons of the objective inconveniences to which they are subject.

The consequence of this is gathering a body of data that are not entirely reliable and which have been collected with a frequency dictated more by logistical problems rather than by a real need of familiarity with the behaviour of the dam.

Automatic acquisition, on the other hand, makes it possible to set a continuous frequency of reading and, above all, to achieve reliability of data that is qualitatively superior to that of manual data.

It is obvious that the absence of total reliability in manual data is to be attributed partly to the inevitable errors in reading. This can be eliminated with an automatic solution. However, human errors may be replaced with errors on the part of the instruments, which therefore need to be constantly kept under control by means of suitable, pre-established checks. Furthermore, it is to be kept in mind that the data gathered from automatic acquisition, are already memorized on supporting equipment that will make easy to process them subsequently.

It is also important to note that by automatic monitoring it is meant not only the gathering of measurement data without human assistance, but also a system capable of executing, on-line and in real time a comparison between the measurement data and similar forecast data provided by the simulation models, so as to be able to check whether their difference is contained or not within a given band of tolerance.

However, it is not to such a comparison that one delegates the responsibility of stating whether a dam is safe or not. This comparison is used only as an instrument placed at our disposal by modern technology, by means of which the situations deemed to be normal are "filed", while the irregular situations (those not meeting the basic hypothesis used by the designer, para 1) are suitably brought to attention. This is done by alerting the management and, depending on the "importance" of the anomaly, putting out "technical warnings" of various levels, to which may be made to correspond times and means of in-depth investigation and/or increasingly more complex interventions.

Viewed in this light, the automatic monitoring system is a "technical filter" which makes it possible for the specialist to concentrate his attention on those structures whose behaviour deviates from the "normal".

Of course, an evaluation of any weight of the structure behaviour can be made by man alone, who with his store of knowledge and experience is in a position to decide whether a given irregular behaviour is to be considered safe or otherwise.

6.1 General Design Criteria of the Automatic System

In designing an automatic control system for a dam, the aim is to put together a modular monitoring system offering flexible features, i. e. that its can be adapted to whatever particular reality as concerns components and functions. This necessity is based on the fact that each dam has its own history and, consequently, it is unlikely that two dams can be deployed with instruments in exactly the same manner.

This necessity should not place economic considerations on a secondary plane. On the contrary, setting up automatic systems designed with standardized criteria and modularity of components should make it possible to offer a correct cost-performance ratio. Furthermore, particular attention is to be placed on the following, when designing and setting up such automatic surveillance systems:

- the choice of the automatic sensors and their deployment on the structure. Each sensor should be tested for performance and reliability;
- the choice of the acquisition network. The network may be concentrated or distributed according to the number and location of the sensors to be scanned;
- the choice of the micro-computer for data acquisition and processing.
- the implementation of the comparison models in the micro-computer. Their routine use should in fact begin only when a suitable validation of the model itself has been executed off-line;
- the need to protect the installation against electromagnetic field interference that could compromise its functionality;
- the choice of system for tele-transmission of the data to a remote center.

6.2 Configuration of the Modular System

Different approaches may be adopted in developing the setting up of a control system on the basis of the requisites cited above.

The standard configuration, illustrated hereafter, has already been assembled, with more or less similar details, for the monitoring of various Italian dams.

6.2.1 General Outline of the Hardware

The modular system is mainly made up of two physically and functionally separate units that are connected together with a line for the exchange of information.

The system therefore consists of a local or peripherical measurement unit and a central one for control.

The measurement unit is given the task of electrical conditioning of the sensors, scanning of the measurement channels, analog/digital conversion of the signals, temporary memorization of the values measured and, finally, the transfer of data to the central acquisition and control unit.

This latter, which is based on a micro-computer, is entrusted by suitable program with all the control functions of the system. These are:

- the acquisition of signals from the measurement unit;
- the execution of diagnostic tests;
- the validation and processing of data;
- the comparison with the threshold limits and the activation of warnings;
- the display, printing and recording of the data acquired;
- their tele-transmission to a remote post.

Joining the two units together makes it possible to set up a system with conspicuous characteristics of functionality and flexibility. This applies both to the hardware, made up of components and modules that embody the various measurements and control units, and also to the software, represented by a series of programmes that are introduced into the memory of the central unit depending on the specific requirements.

6.2.2 General Structure of the Software

On the basis of the specific requirements of the individual installation, the modules necessary for the control of the structure are introduced into the general structure of the main programme.

The main functions of the software system are:

- Automatic start-up of the system
- Continuous monitoring
- "Normal" periodic acquisition
- "Accelerated" periodic acquisition
- Acquisition on the request of the operator
- Comparison with the threshold levels and activations of "technical warning" signals
- Visualization of the measurements and messages
- Printing of the measurements and messages
- Data recording
- Control of the synoptic panels and graphic representations
- Tele-transmission of data to a remote post.
- Diagnostic tests.

7. ANALYSIS OF THE RESULTS

In accordance with the regulations currently in force in Italy, the use of measurement data goes substantially through the following procedure: manual gathering of data; up-dating of the dam records by the keeper; transcription of the data gathered on the structure in records kept in the office responsible for the safety of the structure; periodic manual up-dating of the diagrams of some of the quantities, both for periodic communication to the Control Authorities as also for visualization of the measurements useful for control of the safety of the structure.

The evaluation of such safety is obtained from the visual examination of the diagrams representing the progression of the cause and effect quantities, as also from a search (sometimes only intuitive) for correlations between the said quantities. Should the technical personnel be sufficiently capable, the presence of irregular effects can be evaluated on the basis of this examination. The attempt to show up such irregularities in a more objective manner by means of simple statistical processing, as for instance, averages, moving averages and simplified regressive models, involves considerable work without however offering the assurance of satisfactory results.

This manner of proceeding entails a delay which is not insignificant, for examining the data by technical personnel, and a considerable effort of manual processing. Moreover, the reliability of the measurements and their treatment is not always satisfactory.

7.1 Automatic treatment of the Measurement Data

Over a number of years, attempts have been made in Italy to organize the processing of measurement data by exploiting the potential offered by computer.

This treatment has been sub-divided into two parts on the basis of the following scheme:

- acquisition and an initial processing of the measurement data on-line and in real time (para 6);
- filing in the appropriate measurement data for subsequent off-line elaboration. Suitable Data-Base Structures are used.

In this scheme, the measurements gathered on the dam manually or automatically are sent (by post, teleprinter, telephone, etc.) to the office responsible for the structure. In its turn, this office is equipped with a suitable terminal system via which it is connected to a remote computer center, having at its disposal filing and processing programmes.

In the experience gained until now, a configuration made up of a CRT, a keyboard, a printer, a recorder and a plotter (usable both on- and off-line) represents the correct balance between the cost of the system and the required performance.

The data bases and the interactive systems set up for the filing and treatment of the measurement data make it possible to memorize all the data on the condition of the structure, the instruments installed, the measurements and the results obtained from the processing of all the measurements filed.

In particular, such processing facilitates in:

- filing the raw measurements gathered on the dam;
- transforming these measurements into significant quantities;
- regrouping and printing them and obtaining their diagrams as per pre-established standards;
- carrying out preliminary analyses (averages, moving averages, Fourier Analysis) in order to verify evolutionary trends;
- effecting consistency checks on the redundant measurements;
- searching out correlations between cause and effect quantities, developing various types of regressive models;
- comparing the quantities measured with similar values forecast by the reference models;
- carrying out analysis of deviations between measurements and forecasts.

The automatic processing of data offers the responsible office, the following advantages:

- possibility of making diagrams for all quantities measured on the structure, thus ascertaining their usefulness or otherwise, with consequent rationalization of the measurement plans;
- rapid visualization of each quantity of interest on the basis of graphic formats called for by the user;
- convenient checks of the assumptions of the technical personnel by means of both simple preliminary processing as also of more sophisticated reference models.

7.2 Comparison of Measurement Data with Similar Forecast Data

As stated before, the periodic checks of the structure, to assess the conservation of various structural elements (para 9), combined with the results of the measurements processing and with the comparison of the forecast model, constitute the basis for issuing an objective evaluation of the real strutture behavior.

What follows is a brief review of the comparison models widely employed in Italy:

- "A posteriori" regressive models
  The regressive models are the most familiar among mathematical models, being the most frequently used till recently. They are relatively simple to use, and they do not require elaborate processing. They may be used for checking all of the measured effect quantities (displacements, seepage losses, unitary dilations, rotations, etc.). Setting up such a model requires to have at one's disposal, for a suitable period of time, the chronological series of both cause and effect quantities.
  Statistical models are widely used due to their low cost, the ease with which they are set up, as well as the satisfactory results that can be obtained when the structure does not present particular problems.

- "A priori" deterministic models
  When the correlation between cause and effect is determined via a structural analysis of the dam, the checking of the quantities is carried out by means of an "a priori" deterministic model.
  Besides knowing the geometric parameters of a structure, the construction of a deterministic model also requires a thorough knowledge of the physical-mechanical characteristics of the materials. In the absence of this latter, the model has to be "calibrated" by using the measurement data gathered during a period of normal operation. Besides being a valid tool for checks during normal operation, the deterministic model may also be employed as an instrument for the interpretation of the structure's behaviour in conditions of special operation and/or maintenance.
  It is to be emphasized that by way of drawback, the setting up of a deterministic model calls for a much greater technical and economic committment than the regressive model. Once it is set up, however, it remains a valid, objective and reliable means of comparison with reality in whatever condition of operation of the dam.
  There are some other kind of numerical models; for ex. models realized using together deterministic and regressive technique.

7.3 Processing of the Measurements; Alert Levels

Checking the satisfactory behaviour of a dam by means of a model, is accomplished by ascertaining that the measured quantities do not differ "excessively" from the "theoretical" quantities provided by the reference models under similar ambient conditions.

In other words, should the deviations between the measured values and the ones forecast by the mathematical model be contained within a "band of tolerance", the behaviour of the dam is "normal"; while if some of these deviations fall outside the same band, then the behaviour of the dam is irregular. The "anomaly" of the measurement may derive from a great number of causes, clearly not all of these being dangerous.
Once these causes have been ascertained, then and only then will it be possible to give a correct evaluation on the safety or otherwise of the structure.

In light of realizations being carried out in Italy, the "band of tolerance" has been established on the basis of three bands:

- an initial band within which the forecast-measurement differences should fall, in order to ensure normal behaviour of the structure;
- a second band, which indicates slight within irregularities, should the differences fall outside the first band, but the second one;
- finally, a third band, which is a pointer to suspicions of serious irregularities.

The amplitude of the three bands has been established on the basis of the following criteria:

- calculation of the standard deviation of differences between forecast model and measurement, estimated on the basis of two or three years of normal behaviour of the structure;
- limits of the first band equal to twice the standard deviation;
- limits of the second band equal to three times the standard deviation;
- limits of the third band established by the designer on the basis of ultimate strength data of the physical and/or mathematical model of the structure.

Obviously, the evaluation of the structure behaviour derives not only from the absolute value of deviation from an individual quantity, but also from its evolutionary trend.

Moreover, the possible seriousness of the situation emerges more clearly whenever not only one, but several quantities show an irregular behavior.

8. DAMS IN OPERATION WITHOUT AN ADEQUATE MONITORING SYSTEM

It has been seen in the foregoing that the safety of a dam is ensured by a set of activities that cover the entire period of its life, starting from the initial phase of research and design. However, when the dam is in operation, one is faced with a structure whose history can certainly be re-examined and possibly critized but is surely difficult to change.

To give an assessment of inadequate control of a structure that has been in operation over a lengthly period, means assigning an evaluation of inadequacy (with respect to certain guiding principles) of the existing monitoring system: inadequate from the viewpoint of safety as also from that of the prevention of structural degradations or of the operational ontage of the structure.

For such structures, the inadequacy of the control system may derive mainly from two causes:

- inadequate design (or unsatisfactory setting-up) of the measurement system, either as concerns the number of sensors, the type of quantities checked, or else owing to an incorrect frequency of the measurements effected;

- current condition of the structure's different from that foreseen in the design phase (greater degradation than expected, unforeseen structural or geological phenomena, etc.), so that the monitoring system is no longer adeguate, even though initially it was correct and adeguate.

Faced with this situation, the need arises to resolve the problem of safety by searching out the most objective possible criteria that facilitate in identifying possibly dangerous conditions.

Alongside the re-examination of the routine control, a "certified control" of the structure is called for, which is to be carried out independently of the routine activity.

The "certified control" is based on a "check-up" of the structure aimed at ascertaining the safety and, consequently, at activating the procedures to be followed during the routine control.

With an approach depending on the year of constructing the dam, the activities to be effected during a "certified control" are:

- re-examination of the project, of the documentation on the commissioning and all historical information pertinent to the life of the structure; updating of the project data in accordance with the regulations issued in progress of time by the control Authorities;

- survey of the installed control network, assessment of its completeness and adequacy in relation to the type of structure; preliminary examination of the plottings carried out during the routine checks;

- analysis of the data acquired during past operation of the structure and interpretation of its behavior;

- investigations for the determination of physical-mechanical and geometric characteristics on the structure and foundation;

- assessment of the stability conditions; physical and mathematical modelling of the structure-foundation complex;

- setting up and/or adaption of the forecast models of the static-dynamic behaviour of the structure;

- revision and up-dating of the monitoring and measurement processing system;

- periodic checks on the condition of the materials via non-destructive investigations;

- compilation of a surveillance procedure and/or handbook manual for those responsible for the safety of the structure.

All of these investigations provide for the elements of an objective evaluation of adequacy or otherwise, of the measurement system under scrutiny.

Should this be found to be insufficient, the information gathered makes it possible to redesign a suitable measurement system to achieve effective surveillance. The permanent instrumentation will be brought into line with this new scheme by integrating it or possibly replacing it with more comprehensive and modern devices.

9. NON-REPETITIVE CHECKS

Even when the permanent measurement system, installed on the dam, is found completely adequate for purposes of surveillance, there may occur some circumstances that call for extraordinary investigations. These are normally carried out "ad hoc" and with instrumentation and equipment of non permanent type.

There might be various aims for this type of investigation, among these:

- investigations not executed at the time of construction, because not deemed necessary at the time or beyond the then prevalent state-of-the-art;
- to carry out investigations not feasible with permanent type instrumentations - owing to technical and/or economic reasons;
- investigations intending to survey and quantify a condition of degradation of the materials (artificial or natural) that are suspected or checked only qualitatively.

These latter investigations are of particular relevance, inasmuch that all structures are subjected to the passage of time, and therefore exposed, in greater or lesser measure, to the risk of degradation. Thus, these "special cases" call for a number of considerations, as those set out hereunder.

Deterioration of the dam body can occur by alterations in the physical/mechanical characteristics of the dam materials, (masonry, concrete, or loose material), and/or by a downgrading of the dam's structural integrity.

For rigid masonry dams, the deterioration of the materials is generally caused by original defects in construction (poor quality in bonding, and/or insufficient proportioning of batch quantities), or by external agents (freezing, erosion, or leaching).
The initial spreading points of deterioration can be seen in zones that are weak to begin with (i.e. construction joints, or honeycombs).

The integrity of the structure can be downgraded from crack formation, generally caused by shrinkage, eccessive temperature variability, or differential foundation settlement.

Also in the case of deformable embankment dams, the physical/mechanical properties can change with time. On non-protected facings, erosion phenomena can be produced by surface run-off or exceptionally by surfacing of infiltrating water.
For core and semi-pervious zones made of fine materials or

silty-clays, abnormal variation in water content can occur, both as increase (excess or non-dissipation of pressure) or as decrease (dessication), and cause swelling or shrinkage.
Too large deformations occuring in water-tight zones (core, upstream facing), decrease the safety of the dam.
Crack-like defects can be caused by local imperfections in the construction process, due to insufficient checks on the placement of material or on its origin.

Significant changes in the physical/mechanical characteristics of rock and ground foundation, are generally related to abnormal variation of the ground water surface (seepage, piping, excessive pore pressure, internal erosion, instability of the abutment).

From the forementioned, it is obvious that a reliable evaluation of the conditions for structure deterioration can be formulated only through an in-depth experimental survey of both the dam as well as its foundations.

It is to be noted that the investigations for ascertaining the conditions of deterioration, make it possible to identify and check the quantities and structural elements to be controlled with greater accuracy by means of the measurement system. They also provide an acquisition of parameters required for interventions aimed at consolidation of the dam and its foundation.

As such, the main objectives of the investigations may be summarized as follows:

- evaluation on the conditions of deterioration and physical-mechanical properties of the dam and the foundation materials;
- location of possible cracks, lesions and their geometric characteristics, in particular their extension within the structure;
- assessment of the efficiency of the waterproofing elements (grout curtain, cutoff, upstream face, core);
- diagnosis of the causes of deterioration.

In the case of concrete dams (and relevant foundations), the methods for the execution of the investigations are as follows:

- preliminary visual examination - to assess the situation and indicate the most suitable approach of intervention;
- mechanical coring via continuous boring, with visual examination and classification of the samples;
- permeability tests in the boreholes;
- injection tests in the boreholes;
- prospecting with television probes in the holes - also in possible perforations downstream of the waterproofing screen, for assessment of the waterproofing;
- geophysical surveys; sonic boring and sonic velocities; acoustic emission surveys;
- vibrodyne tests for assessment of the overall dynamic behaviour of the structure;
- strain tests with dilatometer in the boreholes;
- structural survey of the rock mass;
- plate loading tests for assessment of the strain characteristics of the rock mass;
- tests with flat-jacks on surfaces;
- decompression tests;
- laboratory tests on samples obtained during the borehole coring.

In the case of an embankment dam:

- drilling in the dam body and foundations for undisturbed samples;
- boring in the core wall, and in the other water tight structures made of concrete or bituminous conglomerates;
- testing for water absorption inside the boreholes;
- testing with pressuremeter and dilatometer inside the boreholes;
- testing with penetrometer;
- laboratory testing of undisturbed samples.

Execution of some or several of the above-mentioned tests depends on the assessment of the manifestations of degradation or of irregular behaviour in light of the results referred to in para. 6.

The periodic repetition of some of the investigations cited above make it possible, moreover, to verify the possible worsening of the physical-mechanical characteristics of the concrete and the foundation rock.

The results of these investigations might finally lead to articulation of interventions for structural or hydraulic renewal (above ground or in the foundation) or even, in extreme cases, to decommissioning the dam or else its complete redesigning.

10. NEW INSTRUMENTATION

In the field of instrumentation development, considerable effort has been made towards realizing sensor which, besides being reliable and accurate, can also be automated. Special attention should be paid to the validation of measurements effected by the instrument via an autotest.

The main instruments already endowed with automatic reading sensors are:

- the co-ordimeter for plumbline surveys;
- the hydrostatic levelling for the measurement of vertical displacements;
- thermoprobes for temperature surveys;
- hydrostatic scale for measurement of water level and/or seepage lesses;
- strain-gauges for strain surveys (short or long base strain gauges);
- sensors for surveying uplift pressures and/or interstitial pressures;

- collimation for the measurement of horizontal displacements.

In the context of Italian experience, the recent employment of the following items call for a special mention.

10.1 Laser System for Survey of the Dynamic behaviour of the Dam (Ladir)

Laser interferometry has been impressively applied to measure the dynamic displacements of dams. The structure is excited artificially (with vibrodyne) or naturally (with wind, stream immision into the basin, etc.).

Similar to a large topographic instrument on a tripod, the Ladir should be placed on a fixed position outside the structure under study and at a distance not greater than 200 m; it can be pointed in any direction and on any number of points of the structure, without these having to be specifically marked.

The intensity of the laser ray projected, suffices to give the return signal, which is suitably treated and recorded. The quantity measured is the component along the direction of the laser ray of the dynamic displacement of the point of the structure targeted by the ray itself. The simultaneous combination of a second laser head allows to measure a second component of the displacement. The subsequent treatment of the data makes it possible to obtain a considerable series of information similar to those obtained with the accelerometers deployed on the structure but with a rather different operational procedure and, from certain standpoints, rather more advantageous ones.

10.2 System for the infrared Survey of the Surface Thermal Condition (Thermography)

This method facilitates the study of the surface's thermal condition in real time, and even at considerably distances. The response, which is normally provided in a false-color photographic form, may also be easily digitized for all subsequent processing.

This method makes possible an extensive and continuous examination of the observed surface and can show up heat flow phenomena that are inconspicuous and that could easily escape a punctiform examination.

Temperature differences of about 0.2 C can be detected, and it is easy to follow the daily thermal evolution over the entire visible surface of the dam.

11. REGULATIONS IN FORCE AND THEIR POSSIBLE UPDATING

11.1 Regulations in Force

The design, construction and operation of dams come under regulations, passed per the D.P.R. No. 1363, dated November 1, 1959 integrated by the Technical Regulation of D.M. dated 24/3/1982. These entrust the overall supervision in the field of dams to the Dam Service, Technical Department of the Ministry of Public Works, and to the sub-offices of the same ministry, subsequently named Civil Engineering Offices.

In the technical inquiry phase of a project, the Service carries out a consultive function by effecting assessment aimed at ascertaining the correspondence of the design to the requisitions and the technical requirements set out by the "Regulations". It then refers to Section IV of the Public Works Upper Committee with a drawn up report.

The Dam Service may directly proceed with the approval of dam designs of limited importance.

During the inquiry phase, the military authorities with territorial responsibility are to receive a copy of the project, in order to ascertain the compatibility with possible decrees passed in the interests of national defense.

Execution of the project must meet with a list of conditions, detailing regulations concerning:

It is increasingly clear that the visual check and also the measurements carried out by such personnel are not always reliable. For the purpose of an effective evaluation of the structure behaviour that is based on visual inspection, the services of highly specialized personnel are called for, who are able to offer structural competence which is by no means required of dam wardens.

These considerations of a social and technical nature are to be placed alongside the economic ones, inasmuch that the ratio between the benefits obtained and the performance offered by personnel charged with warden's duties might be found to be unsatisfactory with respect to similar costs and results deriving from a more modern and reliable system and one that has less ties to personal problems.

In light of the foregoing and based on the experience acquired in the conditions mentioned above, it would appear that in Italy the time is ripe for an evolution in the systems for dam control. It is in fact in this context that proposals can be made for a guided surveillance system that facilitates in obtaining all the information required at the present time (perhaps more) but in a more reliable manner, that can be utilized with greater ease and with the possibility of pre-filtering of useful information, so as to be able to concentrate attention and means where and when a possible irregularity in the situation so requires.

It is with this view that it is possible to state, that today there is the capability to organize in the case of almost all dams a surveillance articulated along the following lines:

- installation of an automatic television check system of all the points normally involving the current daily inspection visits by the warden, with the possibility of extending the number of areas included in the visual field, and of remote transmission of the images;

- installation of an automatic measurement system for all the quantities currently obtained by the warden, with recording of these on suitable supports maintained at the dam and at the disposal also of the inspectors from the Ministry;
  The frequency of measurement may obviously be easily modified depending on the requirements of the moment, in particular in cases in which checks are kept on behaviour that is considered irregular, and of greater interest in the context of safety;

- possible installation (at the dam site), of a micro-computer capable of comparing the data obtained with the "normal" behaviour of the structure, and offering a preliminary synthetic evaluation thus leading to rapid identification of possible irregulaties;

- teletransmission of all the quantities (or of only a part of then, suitably selected), to a specialized center, where capable technical staff can analyze the data received, deciding on the time and manner of interventions, should such data reveal an irregular condition of the structure;

- execution of periodic visits, every 3-6 months, by a team of technical specialists, whose task is to carry out preventive maintenance of all the instrumentation, together obviously with rapid repair in the event of breakdown;

- execution of periodic visits, every 3-4 weeks, by a team of technicians charged with the overall inspection of the structure, in order to identify possible significant variations in the structure and

It is also the task of the applicant to carry out the controls and the periodic measurements provided for in the list of conditions and in the approved executive design.

An appropriate register should be maintained in the guardhouse and should be keept updated with the following records:

- the control measurements, which in the case of dams of major importance should relate to the strains and displacements of the structure and rock, the internal temperature of the masonry mass, the uplif pressures, or, in the case of embankment dams, to the settlements and piezometric levels in the body of the structure;
- the measurements of the seepage losses through the structure, the rock and the closing components of the outlets;
- the daily measurements of temperature, max. and min.; of rainfall and snow cover; of the water level in the reservoir; of the water temperature at the surface and at a depth of 5 meters; of the thickness of the ice layer, if any; of the meteorological and hydrological (flood) events of particular interest;
- all other measurements that might be deemed necessary;
- a description of ordinary maintenance works, the location and dimensions of possible cracks that may have shown up in the dam and its secondary structures, and the steps taken in this context.

The register is to record from time to time the visits and recommendations of the officers of the Civil Engineering Office and the Dam Service, as well as the results of the checks on the operating mechanisms.

At the end of each month, a bulletin containing the data and measurements cited above is to be forwarded in duplicate to the Civil Engineering Office, which will transmit a copy to the Dam Service.

The efficiency of the outlet elements, also have to be checked in the presence of officers from the Ministry at intervals not excessing six months.

The officers of Civil Engineering Offices, and those responsible for ascertaining signs that may raise doubts on the stability of the dam, have the right to compel the grantee to take those urgent measures, in connection with the operation of the reservoir, they deem indispensable for ensuring public safety.

11.2 Hypothesis of Updating of the Regulations on the Control of Dams in Italy

As mentioned above, current regulations in Italy require that there must be continuous presence at the dam site by one or more wardens. These wardens ensure a constant visual check of the structure, and manually upkeep an appropriate register of measurements called for in the list of conditions. However, in recent years the evolution of socio-economic conditions has increasingly made it difficult to find personnel who are willing to remain isolated, at times for long periods of times, in the guardhouse and far from their families.

- the execution of the project, specifying the manner of building, the works to be carried out for the waterproofing and the possible consolidation of the foundation; the characteristics and source of the materials to be employed and the control tests to which these are to be subjected during the construction, both in the job site laboratories and also in specialized ones, setting out the number and frequency of the sampling to be taken under the control of the Administration;
- observations and measurements to be made for controlling the dam behavior, specifying the various types of equipmènt to be deployed within and outside the structure;
- the surveillance of the structure by the applicant and the control of the Administration during the construction and operation;
- the commissioning-related performance;
- the link-up between the guardhouse, the downstream population centers and the nearest office of the applicant or granter, and for the signalling to be carried out in the event of possible danger and of an order of immediate emptying of the reservoir;
- other measures that are necessary for the satisfactory operation and safety of the structure.

During the phase of construction of the dam, the Dam Service is required to effect a constant activity of supervision of the works, of control of the materials employed, of ensuring that in the building of the artificial reservoir the applicant observes the special technical norms set out by the governing authorities.

The Dam Service participates in the commissioning of the dam and of the related structure. Its task is to provide all of the information pertaining to the structure, and to testify to events that have occured during its construction, as well as during the phase of experimental filling of the reservoir, and all such data that may be useful for the success of the commissioning.

During the operation of the reservoir, it is at all times the task of the Dam Service, with the aid of the Civil Engineering Offices, to carry out surveillance of the structure, via both visits to take place at least twice a year, possibly in conditions of minimum and maximum reservoir levels, as well as periodic visits for checking the efficiency of telephone and radio links, as well as of other possible signal and alarm systems.

During the operation of the reservoir, it is at all times the task of the Dam Service, with the aid also of the Civil Engineering, to carry out surveillance of the structure, via both visits to take place at least twice a year, possibly in conditions of minimum and maximum reservoir levels, as well as periodic visits for checking the efficiency of telephone and ratio links, and of other possible signal and alarm systems.

It is the task of the applicant to ensure that the dam is at all times guarded by suitable personnel who will reside in the immediate vicinity of the guardhouse. The guardhouse is to be linked by telephone or via radio with the pubblic telephone network and the nearest offices of the applicant.

its foundations;

- execution of periodic visits, every 6-8 months, by a team of structural specialists who are capable of carrying out a careful visual survey of the structure and its foundations and, on the basis also of the indications provided by the previous processing of the measurements, giving an assessment of the behaviour of the structure;
- the "guided surveillance" system can obviously be integrated, case by case and according to requirements, by specific measurements in the presence of special phenomenon, and by measurements for which automation is not advisable - e.g. geodetic measurements for the overall control of the structure and the basin, which are generally called for at intervals of a number of years.

12. EXAMPLE

An example of a recently builded (1976-1982) Italian dam is reported here in order to show more effectively what is described in this report.

In this dam an automatic monitoring system has been installed. It is realized following patterns which are in accord with the state of the art.

The Ridracoli arch gravity concrete dam closes off a very wide U-shaped valley at the confluence of the river Bidente with the Celluzze mountain stream in the Tuscan-Romagna Appenines in Italy. The dam consists of a double-curvature arch structure, almost simmetrycal in relation to the main section plane, resting on a pulvino along the total length of the escavation profile.

In the enclosed figures the principles characteristics of the dam and of its monitoring system are reported.

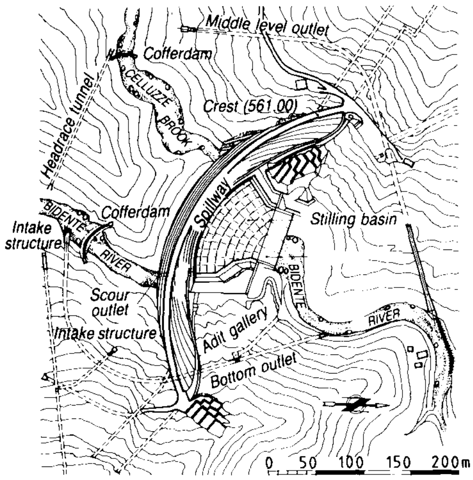
This report was developed by the Italian Committee on Monitoring of Dam and their foundations.

The list of Committee's Members comprises:

Alfredo MARAZIO	Chairman, ISMES
Paolo BONALDI	ISMES
Giovanni CALABRESI	University of Rome
Mariano CUNIETTI	Polytechnic of Milan
Michele FANELLI	ENEL
Enzo GARBUGLIO	SELM
Gabriella GIUSEPPETTI	ENEL
Francesco LIONETTI	AEM
Corrado MAZZON	Consultant
Renato RIBACCHI	University of Rome
Marco RUGEN	Ministry of Public Works
Francesco RUSSO	ENEL
Tito SILVESTRI	ENEL
Carlo TORRI TARELLI	ENEL
Giovanni Vallino	ENEL

RIDRACOLI DAM (PROVINCE OF FORLÌ)
CONSTRUCTION 1976 - 1982

LAYOUT



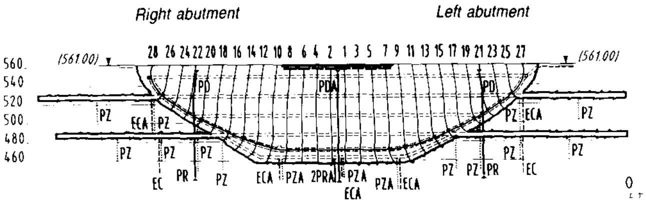
DOUBLE CURVATURE ARCH-GRAVITY DAM

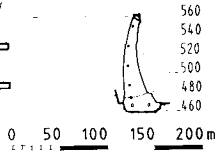
ROCK FOUNDATION BELONGING TO THE MIOCENE
"MARNOSA - ARENACEA" FORMATION

HEIGHT OF DAM	:		103.50 m
CREST LENGTH	:		432.00 m
CROWN SECTION	:	BASE THICKNESS	25.18 m
		CREST THICKNESS	6.62 m
VOLUME OF THE DAM	:		600.000 m^3
STORAGE CAPACITY	:		30×10^6 m^3

UPSTREAM VIEW

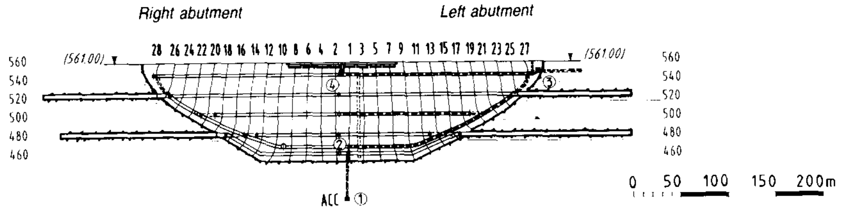
CROWN SECTION





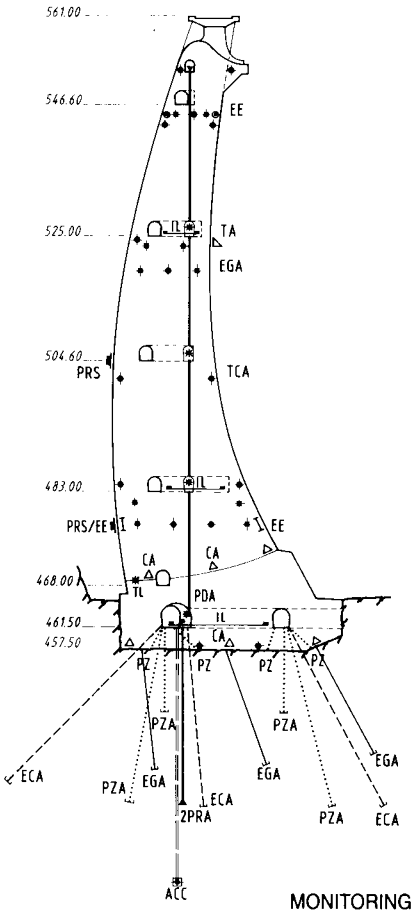
Instrumentation: Rockmeters; Piezometers, Plumblines

UPSTREAM VIEW



Automatic instrumentation for seismic monitoring

CROWN SECTION



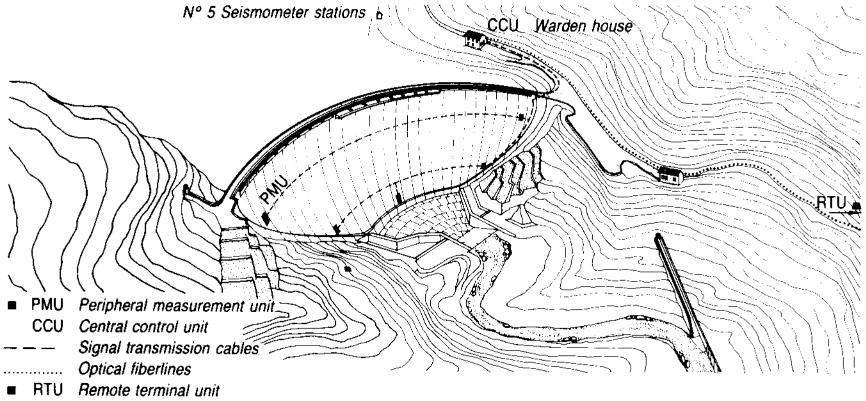
MONITORING SYSTEM

MEASURED QUANTITIES	SENSOR	CODE	NUMBER	FREQ.
STATIC MONITORING				
Meteorological quantities	Thermograph; Barograph;		1	cnt
	Hygrograph; Pluviograph;		1	
	Measuring stick		1	
	Heliograph		1	
	Anemograph		1	
	Electric thermometer	TA	1	plg/A
Water level	Dynamometric balance		1	cnt/A
	Hydrometric staff		1	g
Water temperature on surface and - 5 m	Electric thermometer		2	plg/A
Horizontal displacements				
Dam: 4 direct plumblines	Coordinometer	PD	9	st/ms
	Telecoordinometer	PDA	1	plg/A
Rock: 8 inverted plumblines	Coordinometer	PR	10	st/ms
	Telecoordinometer	PRA	2	plg/A
Geodetic surveys	Distance-measuring		6	ms
	Theodolite		10	trm
Vertical displacements	Level			
Leveling nets crest, galleries, toe, abutments	Level meter	IL	100	ms
Strain				
Dam body	Electric extensometer	EGA	60	plg/A
Rock foundation	Electric extensometer	EGA	9	plg/A
	Rockmeter	ECA	69	ms/plgA
Movements of joints	Dilatometers	TL	33	plg/A
	Removable extensometer	CE	166	bms
Rotations	Vessel level meter	IL	48	ms
Uplifts	Pressure cell	PZA	13	plg/A
	Pressure gauge	PZ	47	st
Stress	Tensiometric capsule	CA	18	plg/A
Temperature dam	Electric thermometer	TCA	58	pls/A
Seepage	Weirs		2	plg/A
	Drains		232	ms
SEISMIC MONITORING	(Automatic)			
Seismic	Accelerometer	ACC	4	
	Electric strain gauge	EE	6	
	Pressure switch	PRS	2	
Microseismic (Area)	Seismometer station	STSM	5	

LEGEND:

cnt	= continuous	g	= daily	plg	= multidaily
A	= automatic	st	= weekly	ms	= monthly
trm	= quarterly	bms	= semimonthly		

MONITORING SYSTEM
PERSPECTIVE VIEW



■ PMU *Peripheral measurement unit*
CCU *Central control unit*
— — — *Signal transmission cables*
.... *Optical fiberlines*
■ RTU *Remote terminal unit*

Appendix F
Annexe F

REPORT BY THE JAPANESE NATIONAL COMMITTEE

INTRODUCTION

Japan has so many high dams amounting about 2 500 that the government and owners have made efforts to ensure the safety of dams, taking account of the following natural and social conditions to be overcome by dam engineering.

Japan Islands are characterized by the following natural and social conditions : Complicated geology, much rainfall, comparatively steep rivers, Pan Pacific seismic zone and populated society.

Safety of dam has been achieved by several kinds of expertized construction, design and guide lines : for examples, design criteria, guide for geological survey, guide for construction manual, and guide for maintenance of dams published in 1973 by JANCOLD.

Regulatory guide by Public Work Research Institute, Ministry of Construction has been presented as the Safety Administration and Monitoring of Dams in 1982. In which the practice of effective instrumentation and monitoring and of adequate analysis of recorded documents are outlined. Other manual and guide were published by Ministry of Agriculture, Forestry and Fisheries, and by the Federation of Electric Power Companies in Japan.

Recently, JANCOLD has reviewed the modern trend of monitoring of Japanese dams and foundations, at the national symposium held in March 1985. This symposium was useful to prepare the presenting national report to ICOLD.

Nevertheless Japan Islands have suffered from frequent seismic shocks, the modern high dams after the second World War have been remained safety without any fatal collapse, excepting a tailings dam.

However, it should be emphasized that the technology of monitoring of deteriorating dams and foundations is becoming important year by year.

1. ROLE OF MONITORING OF DAMS RELATED TO SAFETY

Frequent severe seismic shocks to dams were experienced in Japan Islands, which have been accounted over 45 earthquakes having M 6.4 — M 8.1, since 1943 to 1980. However, dams have existed safely without any fatal damages.

It is most effective in ensuring the safety of dam and its foundation to monitor the leakage while initial impounding and unusual deformation. The judgement of safety of specific dam should be set at every site based on the specific conditions, according to the exact recoreds of usual continuous monitoring. The reliability of the judgement is based on the exact data base which has been evaluated from the usual and continuous monitoring.

Several monitorings should be made to judge the safety of dams during the several periods and at the unusual events : first impounding, ensuring of soundness after completion, deterioration for long term, flood, seismic shock, rapid draw down of reservoir and other unexpected events of instrumentation and monitoring.

So many dams have been constructed amounting about 2 500 in Japan and they have suffered from seismic shocks. Most severe seismic shocks at the rock foundation have been experienced up to about 500 cm/s^2 of instantaneous peak acceleration, according to the empirical formula relating to the expected acceleration with magnitude and epicentral distance, for a few dams.

Any fatal leakage has not been recognized around the dams after such severe seismic shocks. Some unusual leakages from the dam foundations were experienced, but these were quickly repaired by grouting around such locations of leakages as faults and fractured zones in the foundation rock.

It has been generally usual that many dams were experienced seismic shock of a few cm/s^2 for every several years. Aseismic design base has been established for several regions of seismicity in Japan. Pseudo static seismic coefficients are 0.10 — 0.20 for concrete gravity dams and fill dams, and 0.24 — 0.40 for concrete arch dams, which have been reviewed based on the dynamic behaviour of dams and properties of materials of several kinds of dams during earthquake. Modern dams which have been designed and constructed based on the design criteria have been recognized safety even in the severe earthquakes.

2. ITEMS AND INSTRUMENTATION OF MONITORING

Dam and surrounding should be monitored by adequate items in order to ensure the safety of dam, as Table 2.1.

Table 2.1

Elements and Design Parameters Related to the Safety

	Elements	Design Parameters	Items of Monitoring
Hydrology	Rainfall and water flow	Flood discharge, reservoir water level and land slide	Water level in reservoir, spillway, discharge and slope stability
Meteorology	Atmospheric temperature and water temperature	Thermal stress and displacement	Temperature, stress, strain and displacement
Earthquake	Permeability, stability and sedimentation	Leakage, drainage, pore water pressure, uplift, displacement and settlement	Leakage, drainage, pore water pressure, uplift, piezometric heights, displacement, strain, stress and land slide
Construction	Concrete placing, embankment and foundation treatment	Cracking, stress, pore water pressure and displacement	Strain, stress, displacement, pore water pressure and temperature
Operation of reservoir	Impounding, flood control, pumping up and rapid draw down and stability of embankment	Land slide, leakage and displacement	Water level in reservoir, discharge, land slide, leakage, piezometric height, pore water pressure, uplift, displacement, strain, stress and soil pressure

3. SEISMIC OBSERVATION SYSTEM

Seismic observation system has been rapidly improved, particularly in the data acquisition system using electro-magnetic recorder for multi channel data collection. Table 3.1 shows an example of automatic seismograph system.

1) System design of seismograph

Followings are desired in measurement system during earthquake :

1) broad frequency zone to be observed (Fig. 3.2);
2) improvement of reliability of observed wave signal (Table 3.1);
3) widening of dynamic range (Table 3.2). The dynamic range means the amplitude ratio of the maximum to the minimum;
4) record of the absolute time (Table 3.2);
5) recording from the initial behaviour of primary wave;
6) conversion of analogous signal to digital record.

2) Adaptation of accelerometer, velocity meter and displacement meter :

1) accelerometer is the most reliable for wider frequency zone among the other meters, and is applicable to the dam engineering;
2) velocity meter is used to the geologic survey by means of the elastic wave measurement, and also to the geoscience of far distant earthquake and natural oscillation of the earth in the long period;
3) displacement meter is usually designed as the integration apparatus of electro magnetic velocity meter and is used to the geoscience.

3) Acceleration and integrated velocity from the meter as well as pore pressure and strain are useful to the seismic analysis of the dam engineering.

Table 2.2

Merits and Demerits, and the Countermeasures of Automated Monitoring System of Dams

Merits of automation	Demerits of automation and countermeasures
1. Continuous measurement and inspection are possible, then the change of the safety of dam is easier to understand. 2. Labour cost are decreasing in measurement and data processing. 3. Labourous data analyses are possible in precise and rapid manner. 4. Automated graphics are helpful to understand the instant change of behaviour of dam. 5. A lot of monitored data is compactly filed. 6. Warning can be rapidly informed to the people in downstream district at the several kinds of warning levels.	1. Incorrect information takes place from the wrong maintenance of monitoring sensers. Reliable and constant maintenance of monitoring sensers are essential in automation. 2. Improvement of data processing design is usual, then expert of system engineering is necessary. 3. Manual inspection or maintenance of trouble in transmission is essential at the time of lightening, shut down of electricity and typhoon. 4. Too much progress in automation might mitigate the human ability on the macroscopic or adequate judgement of the safety of dam at the accident beyond the design basis. Then well planned training for the hypothetical emergency is essential. 5. Maintenance of switch box is important to increase the reliability, because the junctions are apt to be corrosive. The maintenance should be performed twice a year. 6. Total system should be maintained once a year. 7. Mechanical instruments should be maintained based on the specific maintenance guide.

Table 3.1

Design Basis of Seismic Transducers

Model Parameter	SMAC-B	V-401BT	PV-20A	SDA-240
Mechanism	Mechanic	Servomechanic	Piezo electric	Servomechanic
Maximum observable acc. ..	1 G	2 G	7 G	1 G
Observable period	0.1-10 Hz	0.1-400 Hz	0.1-1 000 Hz	0.1-30 Hz
Sensivity		3 V/G	1 V/1 000 Gal	10 V/G
Analysable acc.	10^{-5} G	5×10^{-4} G	3×10^{-5} G	1×10^{-6} G
Linearity		0.05 %	0.1 %	
Lateral sensitivity		0.1 %	1 %	
Temp. factor		0.001 G. °C		
Temp. sensitivity		0.02 %/°C	0.05 %/°C	
Temperature	−10 ~ 50 °C	−40 ~ 80 °C	0 ~ 40 °C	−20 ~ 50 °C
Shock tolerance		20 G	40 G	
Electric resistance		3 Ωk	1 Ω	100 Ω
Electricity	DC 12 V (B2)	DC 24V, 30mA	DC 12V, 1.5mA	DC ± 12 V

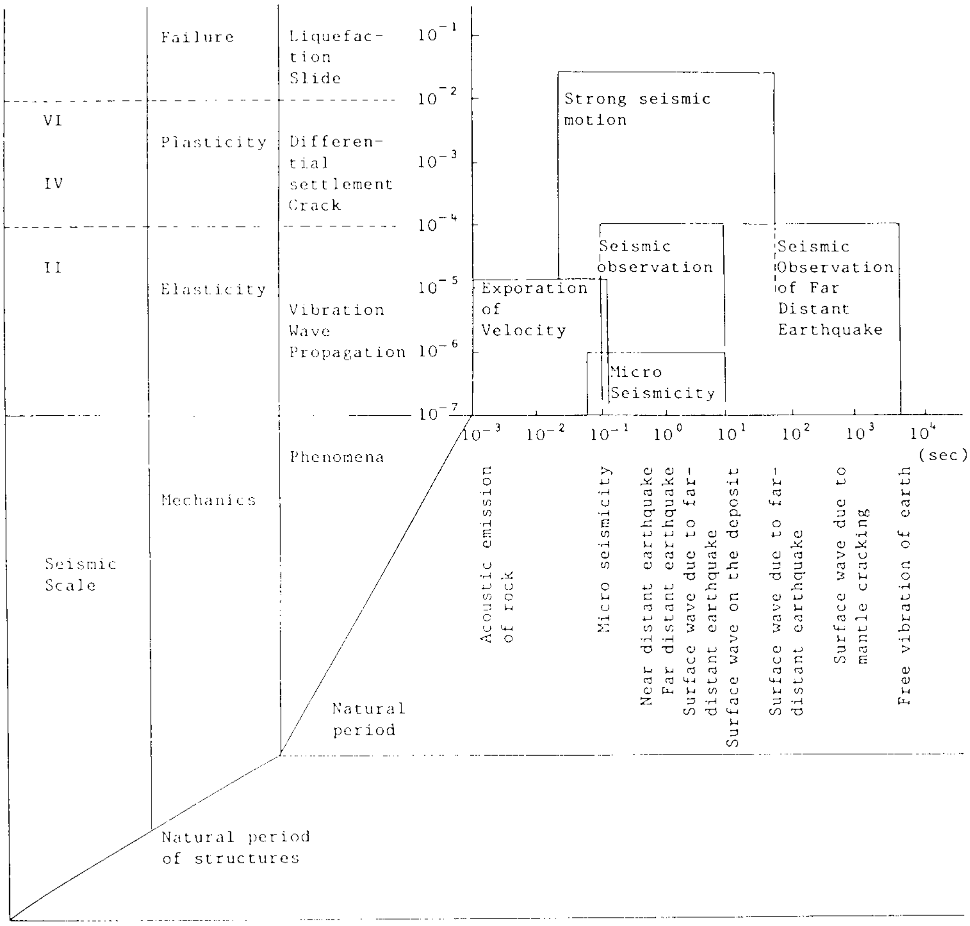


Fig. 3.2
Natural Periods and Strain

Table 3.2

Seismic Recorder

Design basic	Model	SMAD-1	DACS-M	SAMTAC-17 S
Recorder	Media	Digital cassette	Digital cartrige	Digital cartrige
	Density	853 BPI	6 400 BPI	
	Time	30.45 min	60 min	30 min
Input	Channel	3 ch	3 ch	3 ch
	Amplifier	Gain ranging (xl, xl/4)	BGA (12 dB/step)	
	Maximum	± 3, ± 6 V	± 5 V	± 1 000 Gal
A/D transducer	Analysis	12 bit	14 bit	16 bit
	Dynamic range	78 dB	114 dB	
	Sampling	100 Hz	200 Hz	200 Hz
	Period	0.03-25 Hz	0.05-100 Hz	0.1-30 Hz
Retardation time		10.24 s	40 s	5 s
Trigger		1 ~ 16 gal		
Monitor			Analog	Analog
Time	Timing	Date, second	Date, second	
	Precision	±0.005 s	2×10^{-9} s	± 0.005 s
	Correction	Radio time	Radio time	
Information		Record No.	Record No.	Mechanism No.
Electricity	Electricity	DC ± 14.4 V	AC 100 V	AC 100 V
	Consumption		3 A	
	Charge	Floating	Floating	
Temperature		0° ~ 40 °C	5° ~ 40 °C	0° ~ 40 °C
Package	Volume	250 × 400 × 210 mm	535 × 770 × 1 800 mm	

4. MAIN KNOWLEDGE OBTAINED BY MONITORING OF DAMS IN JAPAN

Main knowledge obtained by monitoring is summarized in Table 4 which were instructive to revise the planning, investigation, test, study, design, construction, safety administration, and criteria.

Table 4

Main Knowledge Obtained by Monitoring

	Load	Dam	Foundation	Main knowledge of behaviour of dams
Concrete dam	Hydro-dynamic pressure	●		Westergaard formula was approved by the monitoring at Tagokura dam
	Uplift		●	Uplift pressure in downstream side of curtain grout wall can be reduced by 20 percent of reservoir head, by means of drain holes (Ohishi dam).
Hollow gravity dam	Temperature change	●	●	Deflection toward upstream is dominant in the first stage of impounding caused by the rock deformation of reservoir. Temperature affects sensitively to the dam deflection (Hatanaghi I dam).
	Seismic force	●		Vibration of web plate is dominant and the dynamic behaviour can be verified by model test (Hatanaghi I dam).
Arch dam	External temperature change	●		External change of temperature sensitively affects to the deflection and stress (Nagawado, Yaghisawa and Managawa dams).
	Pore pressure in rocks	●	●	Annual change of pore pressure in rock foundation affects to the changes of deflection and stress in arch dam (Kurobe dam).
	Seismic force	●		Acceleration is amplified from foundation to the crest. Damping coefficient is rather few in vibration test than actual earthquake (Kurobe dam).
Rockfill dam	Pore pressure in soil core	●	●	Pore pressure in soil core rapidly decreases near the abutment. Vertical soil pressure is relatively small compared with the one in rigid filter zone (Tedorigawa dam).
	Seismic force	●		Surface acceleration of rock fill slope fairely increases than inner part. The factor of amplification depends on the input earthquake (Kisenyama dam).
Earth dam	Banking		●	Weathered soil at the upper abutment was cracked by the tensile stress due to the banking and settlement of dam (Fukada dam).
	Seismic force			Amplification of acceleration can be verified by the observation and FEM analysis. However strong motion is not yet experienced (Fukada dam).

5. MONITORING OF DETERIORATED DAM (MARUNUMA DAM)

Marunuma dam was completed in 1930 and was buttress type with 32 m height. This dam is located at EL 1 400 m. There appeared many crackings in the upstream part made of the reinforced concrete deck and much leakage occurred from the joints between the deck plates and supporting walls.

This renewal construction was completed in 1969.

During the monitoring of the deteriorated dam, many kinds of measurements and tests were carried out from 1953 to 1968 as follows.

1) Buttress dam :

- chemical analysis of cored concrete;
- compressive and sonic tests of cored concrete;
- measurements by strain gauges, reinforced gauges, and joint gauges during reservoir operation;
- measurement of dam deflection;
- survey of opening crack.

2) Foundation :

- geology;
- permeability;
- leakage.

3) Judgement :

- causes of deterioration : Crackings were developing due to the freezing and thawing of reinforced concrete deck with 0.54 — 1.47 m in thickness and due to the differential movement of heterogeneous rock foundation;
- deterioration of cracked concrete : Leakage water drew out the calcium in concrete and resulted to deteriorate the reinforcement;
- renewal of concrete plate : The new concrete plate was covered over the deteriorated deck in 1968-1969 and compressed by post tensioning to resist the water load.

6. SEISMIC BEHAVIOUR OF DAMS AND FOUNDATIONS IN JAPAN

6.1. Hydro-dynamic Pressure of Gravity Dam During Earthquake (Tagokura Dam)

1) Observation System of Hydro-Dynamic Pressure on the Upstream Face of Dam (Fig. 6.1.1.)

Five dynamic water pressure gauges have been installed on the upstream face, as well as one accelerometer and thirteen dynamic displacement meters. Tagokura dam was constructed by Electric Power Development Company Ltd. and has 145 m in height and 477 m in crest length. This precise hydro-dynamic pressure gauge has been developed by Prof. Den N.

2) Assumption of Westergaard Formula

Well known Westergaard formula in design criteria in current even in Japan is theoretically available for the longer period of earthquake than resonance oscillation period of reservoir. This formula describes the parabolic distribution with the maximum value of pressure having 7/8 of seismic coefficient of dam body multiplying hydro-static pressure. This assumption of period and value has been verified based on the theory and evaluation of observed data, as follows.

3) Theoretical Background

General theory and interaction theory among dam-reservoir-ground have been developed by researchers, which show that the reservoir resonances at the period of ground motion when the twice of traveling time of sonic wave in reservoir coincides with the period of ground motion or when 1/3, 1/5 of the above mentioned traveling time coincides with the period.

Observed data have been recognized that the resonating pressure or phase difference of hydro-dynamic pressure of dam has not occurred during actual earthquakes. This has been explained by the reason of the absorption of sonic wave on the reservoir bottom.

The theories show that the Westergaard formulation corresponds to the assumption of incompressive fluid in which phase difference between dam and reservoir oscillations could not take place.

4) Verification of the Assumption

Observed relations of periods and phase differences in Table 6.1.1 verifies the assumptions of the Westergaard formula. Fig. 6.1.2 shows the relation between hydro-dynamic pressure and displacement of dam.

6.2. Dynamic Period of Web Structure of Hollow Gravity Dam During Earthquake (Hatanaghi No. I Dam)

Seven horizontal accelerometers, two vertical accelerometers as well as three dynamic displacement meters in Fig. 6.2.1 were observed in Hatanaghi No. I dam which was constructed in 1962 by Chuubu Electric Power Company.

1) Observed Period

Experienced max peak accelerations were 8 cm/s^2 at the rock foundation and 30 cm/s^2 at the crest. Vibration during earthquakes were fairly periodic with 7.2 Hz.

2) Comparison of Period between Model Experiment and Observation

This dam has been studied by the model test on shaking experiments which have shown the 6.5 Hz is predominant period in model, which is practically consistent with the observed natural period 7.2 Hz.

6.3. Seismic Behaviour of Arch Dam (Kurobe Dam)

Horizontal and vertical accelerometers have been installed at Kurobe dam as shown in Fig. 6.3.1. This dam is the highest dam in Japan having 186 m in height and this was completed in 1963 by Kansai Electric Power Company.

1) Observed Max Peak Accelerations

The first impounding has been begun before completion of dam construction at the construction height 3/4 below the design crest of dam. Seismic shock has been experienced 166 cm/s^2 at the rock foundation just downstream of the dam in Aug. 19th, 1961. Dam was inspected safely.

Observed maximum peak acceleration 118 cm/s^2 at the crest has taken place in the near field earthquake in Sep. 8th, 1972, having M 3.9 and epicentral distance 12.8 km. Following are analyzed.

2) Ground Motion

Horizontal and vertical motions were nearly equal at the ground.

3) Amplification of Acceleration in Dam Body (Fig. 6.3.2)

Factors of amplification of acceleration 118 cm/s^2 at the crest are respectively about 3.5 to foundation base and about 1.8 to abutment. Therefore, vibration model was multi-input type at the perimetrical surface.

Vertical acceleration at the crest was about 2/3 of horizontal 118 cm/s^2. This acceleration was respectively 2.4 times foundation base and 3.6 times to abutment (Table 6.3.1).

4) Damping Coefficient

Observed damping coefficients were expected 0.15-0.20 at 3.5 Hz, 0.08-0.09 at 7.0-7.5 Hz and 0.09 at 9.2 Hz according to the power spectrum of responsing accelerations.

These observed ones were fairly larger than the ones which were 0.03-0.11 at the artificial vibration test by the eccentric centrifugal exciter at the crest. It is due to the differencies of vibrating mass and energy between the natural earthquake and artificial excitation.

6.4. Seismic Behaviour of Rockfill Dam (Kisenyama Dam)

19 horizontal accelerometers, 2 vertical accelerometers and 8 horizontal displacement meters were installed in Kisenyama dam which was constructed by Kansai Electric Power Company and has 91 m in height (Fig. 6.4.1.).

Over one hundred seismic records were observed since 1969. The maximum peak acceleration at the base rock was 12.2 cm/s^2 in the far field earthquake, Sep. 9th, 1969, with M 7, epicentral distance 145 km. Followings were analyzed.

1) Predominant Frequency at the Base Rock

Clear predominant frequencies were recognized at 1 Hz and 3 Hz (Fig. 6.4.2).

2) Resonant Frequency of Dam Body

According to the power spectrum of the acceleration and displacement of the earthquake, the resonant frequency was about 2.1 Hz for full water level. It was 1.9 Hz for the low water level at the other earthquake (Fig. 6.4.3).

3) Factor of Amplification in Dam Body

This factor decreases depending on the input acceleration, and is 92/12 or 7.6 (Fig. 6.4.4).

4) Dynamic Soil Pressure

Table 6.4.1 expresses the static and dynamic soil pressures at three earthquakes. Instrumentation is shown in Fig. 6.4.5. The ratio of dynamic to static soil pressure is shown in Fig. 6.4.6 and is recognized about 10 percents.

5) Dynamic Pore Water Pressure

Pore water pressure gauges are denoted by P in Table 6.4.1. The maximum dynamic pore water pressure was 0.17 kg.f/cm^2 at P-25. These dynamic pore water pressures had taken place at the time of the max acceleration or during a few seconds after the time.

6) Comparison of Vibration Modes of Analysis and Observation

The analyzed mode of vibration is based on the assumption of elasticity of shear strain level $1 \times 10^{-6} - 1 \times 10^{-5}$. The result is fairly monotoneous compared with the distinct variational mode of observation (Fig. 6.4.7).

It has been recognized that the softening of rigidity at the top and surface zones is necessary in analysis even at the medium earthquake.

7) Study of Material Property of Rockfill Dam

Material property greatly depends on the initial confining pressure and water submerging conditions, and also on the dynamic strain range. The study had been initiated from the construction of Kisenyama dam.

6.5 Seismic Behaviour of Combined Dam of Concrete Gravity and Rockfill Sections (Gosho Dam)

Accelerations 5-8 cm/s^2 at the base rock and about 30 cm/s^2 at the dam crest were observed during both earthquakes in Dec. 1981 and May 1983 in Gosho dam which was completed in 1981 by Ministry of Construction (Fig. 6.5.1).

1) Leakage

Leakage after the Mid-Sea Japan Earthquake increased only 9 l/min compared with usual leakage 320 l/min and was occupied by the leakage through fill dam and foundation. Three days later previous quantity of leakage is observed. Increased amount of leakage from the gravity section was 0.2 l/min.

2) Dynamic Soil Pressure

Soil pressure, pore water pressure and relative displacement are observed during the earthquake (Fig. 6.5.1). Dynamic soil pressure was 0.1—0.2 kg.f/cm^2.

6.6. Seismic Behaviour of Rockfill Dam with Surface Pavement (Tataraghi Dam)

Fourteen horizontal accelerometers, two vertical accelerometers and three horizontal displacement meters are installed in Tataraghi dam which was completed by Kansai Electric Power Company and has 64.5 m in height (Fig. 6.6.1). The dam has experienced 57 seismic shocks since 1973.

1) Amplification of Response (Fig. 6.6.2)

Amplification of acceleration decreases with the increase of base acceleration and ratio is about 3-10 for the range of base acceleration 0.2-12.6 cm/s^2.

2) Resonant Frequency of Dam Body (Fig. 6.6.3)

The dam suffered from seismic shock on Dec. 28th in 1979 which was M 4.9 epicentral distance 45 km, depth 20 km. Reservoir level was EL. 224.96 m.

The first modes were 2.6 Hz in river direction, 2.8 Hz in dam axial direction and 4.2 Hz in vertical direction.

6.7. Seismic Behaviour of Earth Dam (Fukada Dam)

9 strong seismometers, 18 accelerometers and 4 displacement meters were installed in Fukada dam which has 55.5 m in height and 340 m in crest length (Fig. 6.7.1).

1) Seismic Records

Dam base had suffered from the seismic shock 35 cm/s^2 in river direction during the earthquake M 7.5 in Miyaghioki earthquake on June 12th, 1978, epicentral distance 220 km. Seismograph on the crest had recorded 210 cm/s^2 in river direction which is about 6 times of base acceleration. Power spectrum of acceleration at base shows the peaking frequencies at 2 Hz, 3.5 Hz and 4.5 Hz (Fig. 6.7.2).

2) Settlement after the Earthquake

Reservoir was empty during the earthquake, because the dam was before impounding. Neither crack or sliding on dam were recognized after the seismic shock. However, the crest of dam had settled 2.5 cm and bed rock had settled about 1.0 cm (Fig. 6.7.3)

3) Response analysis

Dynamic response analysis was assumed elasticity, having 5 220 kg.f/cm^2 in Young's modulus, 0.4 in Poisson's ratio and 1.95 t/m^3 in unit volume weight, and 5 % in Reileigh damping coefficient. Reason of elastic assumption is why the working dynamic shear strains were almost limited to the small strain of $1 \times 10^{-6} - 1 \times 10^{-5}$.

Time sequence of dynamic response at the crest coincides in each other of observation and calculation, as shown in Fig. 6.7.4. The dominant frequency at the crest was 1.9 — 2.0 Hz which was filter during the path through the dam body as shown in Fig. 6.7.5.

7. ADVANCED INSTRUMENTATION IN THE NEAR FUTURE

7.1. Optical Fibre Cable

1) Purpose

It is important to protect the monitoring system from the lightening accident as well as to countermeasure the noises, and also to increase the information.

2) Merits

Optical fibre system will contribute to the essential improvement of countermeasurement against the lightening and to effective transmission of many informations. Technology is characterized as follows.

1. The digital signals are easily multi-channeled and transmitted in co-channel.
2. The ratio S/N is low and loss of signal is small, then transmit distance becomes long.
3. Accumulation of noise is small and the correction of signal is easy, and then high reliable transmission is possible.

4. Graphic signal can be reliably transmitted due to the wider frequency zone, low damping and no inductive noise.

5. Graphic monitoring of dam made possible by means of the optical fibre system.

7.2. Ultra Red Laser for Distance Measurement

Underground Triangular Survey at the abutment of Kurobe arch dam was carried out using the stainless double tube in inspection gallery.

Automation of distance measurement will be expected by the ultra red laser, which will be useful to more reliable monitoring and more cost saving.

7.3. Remote Control Robot System of Submerged Inspection of Dams and Aqueducts

The Tokyo Electric Power Co., Inc. has developed the submerged robot system to inspect the dam, gate, pier, aqueduct, foundation rock and slopes. This system achieved more safe, effective and precise inspection (Fig. 10.1).

CONCLUSION

1) Safety of dams in Japan : It has been recognized that there are many high dams about 2 500 in Japan. There are complicated geologic structures and seismic zones, but any fatal damages of modern dam has not occurred.

The safety of dams has been ensured by a lot of experiences and studies, expertized criteria, guide lines and manuals for design, survey and careful construction, as well as monitoring of dams. The Japanese government is taking fairly conservative policy for the safety of the dams.

2) Key points of monitoring of dams : Most essential points of monitoring are leakage and deformation. Particularly, first impounding and earthquake should be careful to inspect the weak points of dams and their foundations.

3) Problems to be developed for the advanced design of dams :

— viscous and plastic deformations of embankment and weathered rock mass during the repeated loading;

— dynamic damping in concrete blocks or jointed rock masses;

— monitoring of deteriorating dams.

ACKNOWLEDGEMENT

This national document is based on the scientific and technologic fruits of many Japanese engineers of JANCOLD. The authors would sincerely appreciate their expertized experiences and knowledges on the safety of dams in Japan, and hope to be useful for the ICOLD.

Committee of Monitoring,

Japanese National Committee on Large Dams

Chairman :	Masao HAYASHI	Central Research Institute of Electric Power Industry.
Member :	Kozo SAITO	Public Works Research Institute, Ministry of Construction
	Masami YASUNAKA	National Research Institute of Agricultural Engineering, Ministry of Agriculture, Forestry and Fisheries
	Hideki HAYASHI and Mitsuo MIURA	Research Institute, Water Resources Development Corporation
	Kenichiro EGAWA	Tokyo Electric Power Company Ltd.
	Masahiro MORINO	Chuubu Electric Power Company Ltd.
	Akio DAICHO	Kansai Electric Power Company Ltd.
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Cooperation :	Takashi SATO and Susumu KANNO	Kyowa Electric Instruments Company
	Koji HARIO	Sakata Electric Instrument Company Ltd.
	Noboru MARUYAMA	Katsushima Manufacturing Company Ltd.

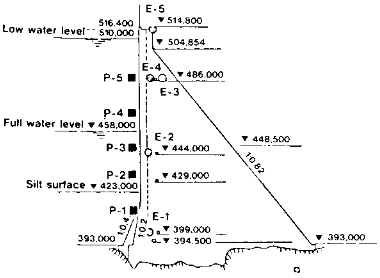


Fig 6-1-1 Hydro—Dynamic Measurements

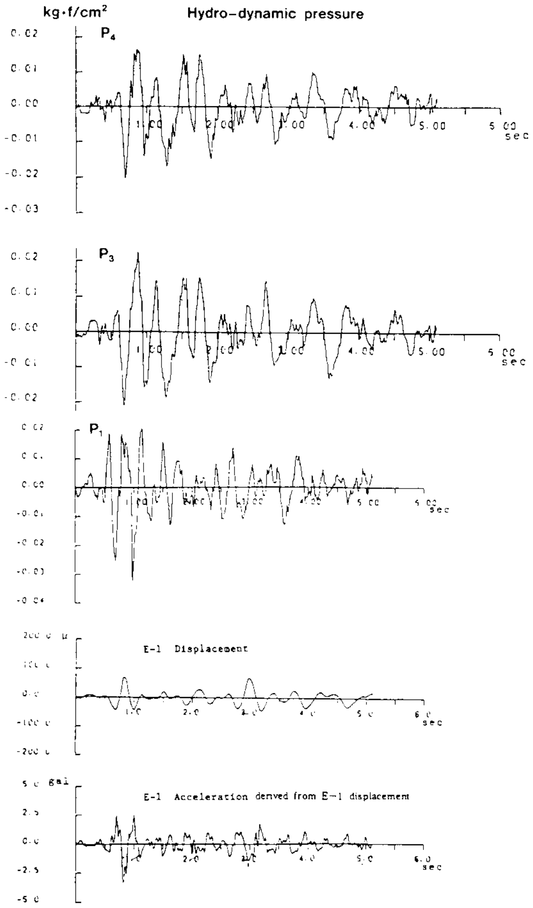


Fig 6- 1-2 Hydro—Dynamic Pressure and Displacement of Dam

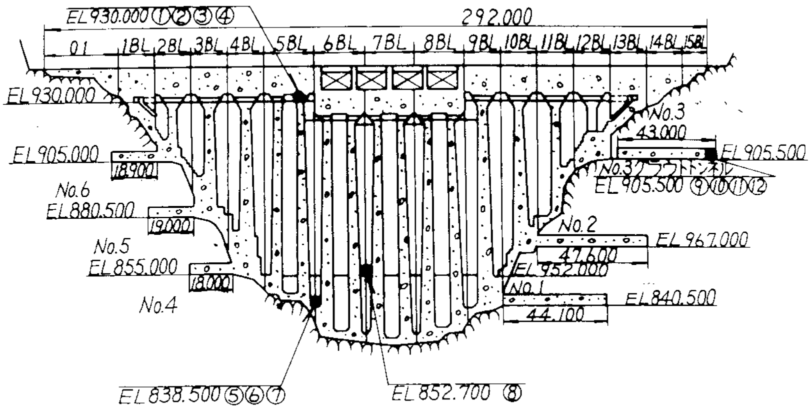


Fig 6-2-1 Seismo Meters

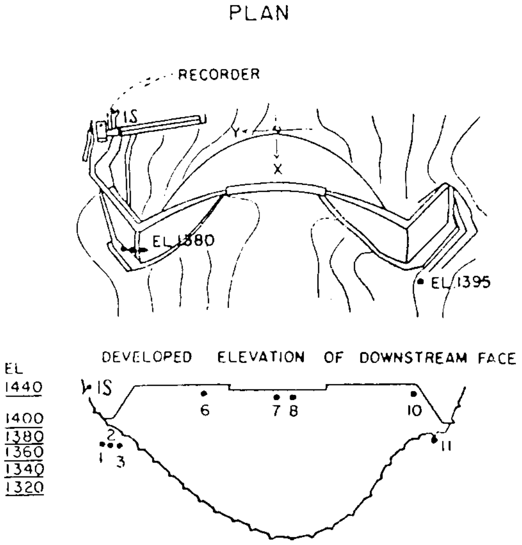


Fig 6-3-1 Seismo Meters

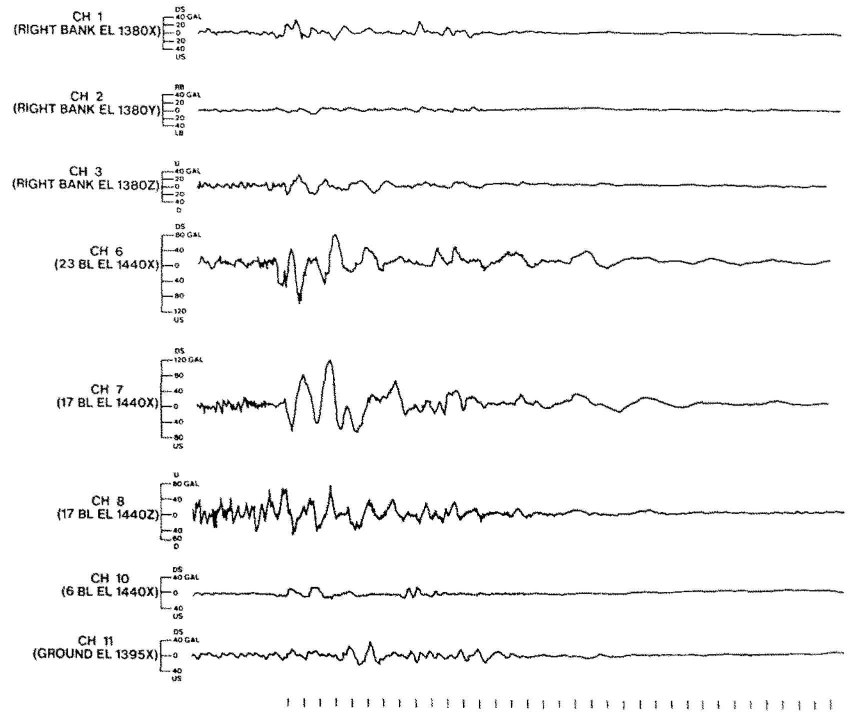
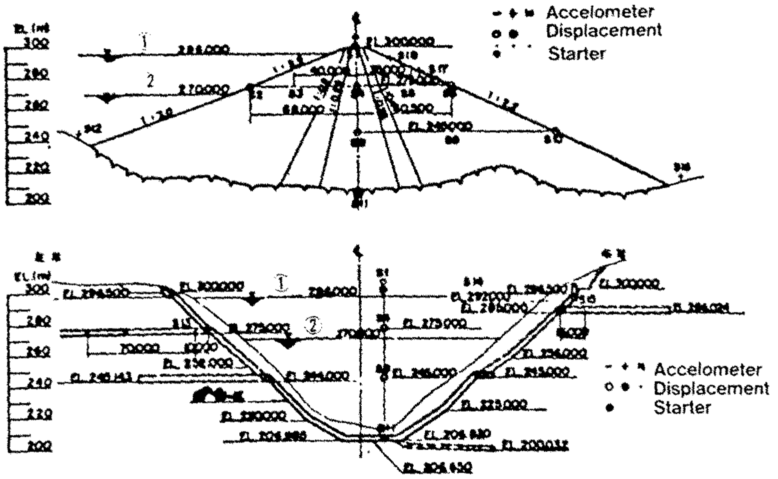
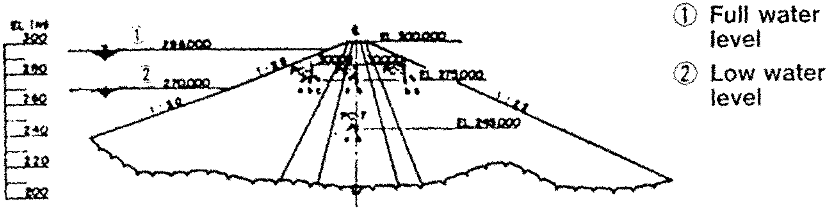


Fig 6-3-2 Seismic Records

Seismo meter



Dynamic soil pressure gauge



Dynamic pore water pressure gauge

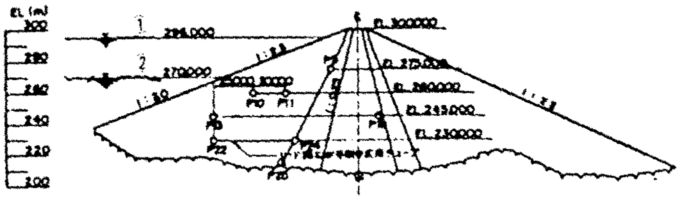


Fig 6-4-1 Seismo Meters

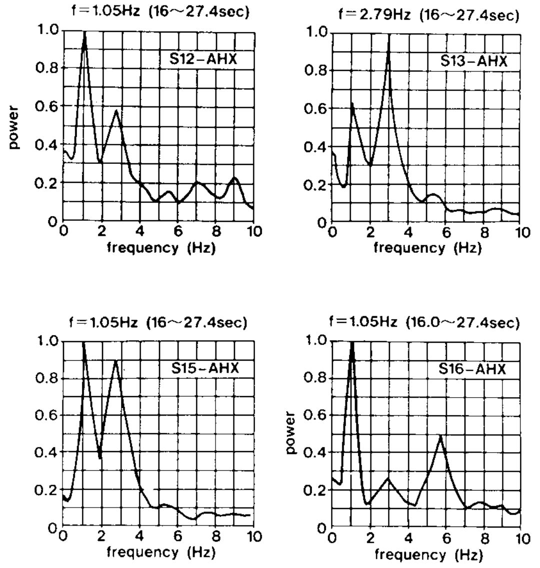


Fig 6-4-2 Power Spectrum of Base Rock Motion

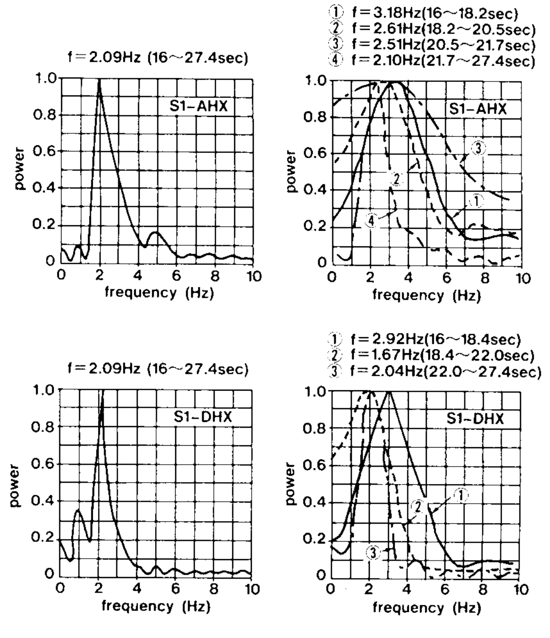


Fig 6-4-3 Power—Spectrum of Motion of Dam Body

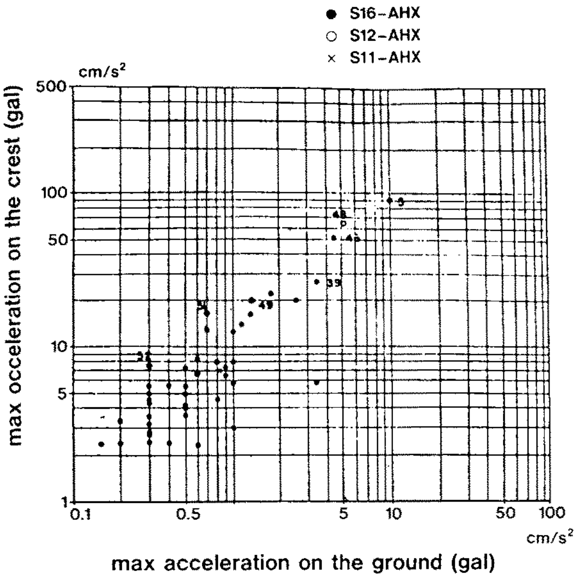


Fig 6-4-4 Amplication of Response

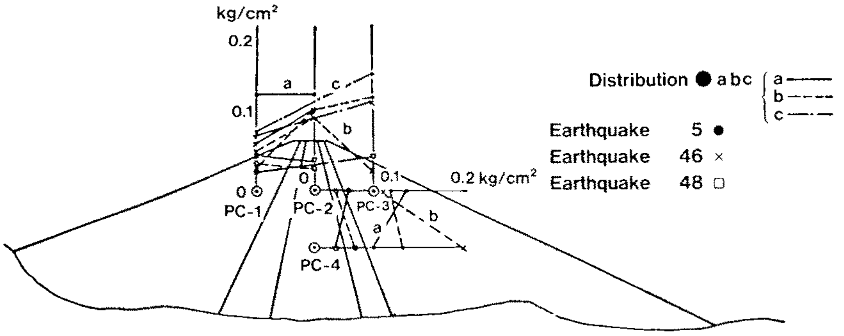


Fig 6-4-5 Soil Pressure during Earthquake

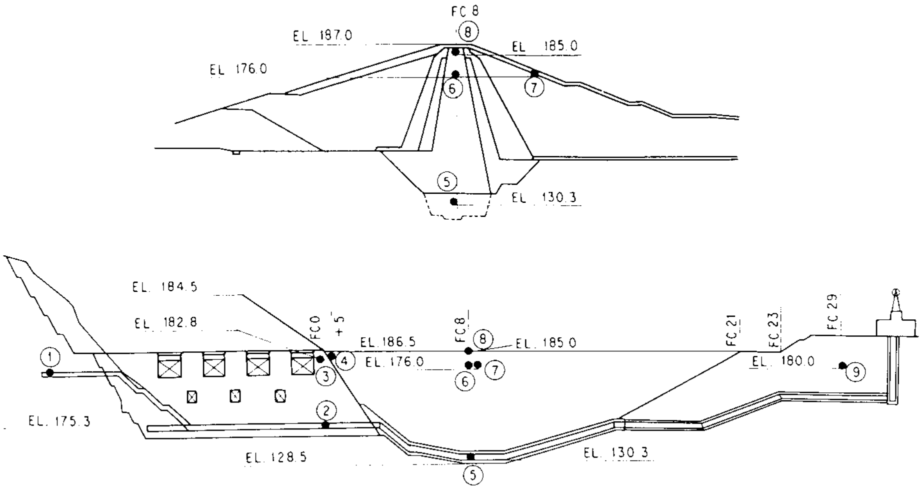


Fig 6-5-1 Gosho Dam

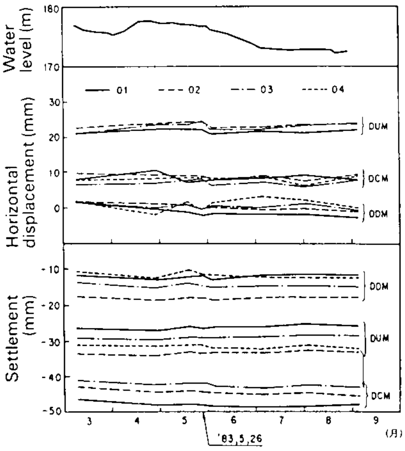


Fig 6-5-2 Deformation after
Earthquake May 1983,

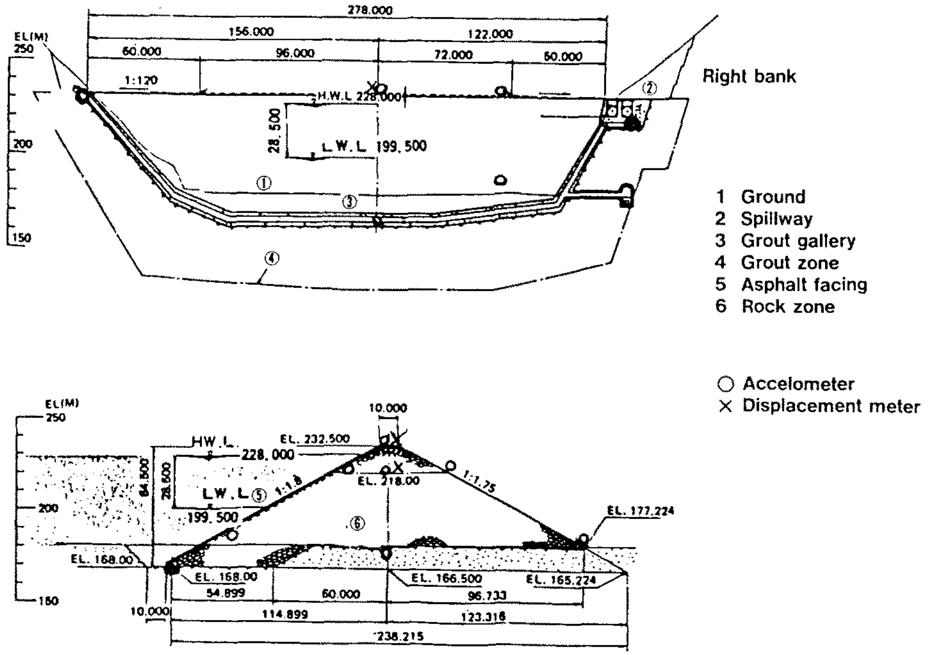


Fig 6-6-1 Seismo Meters

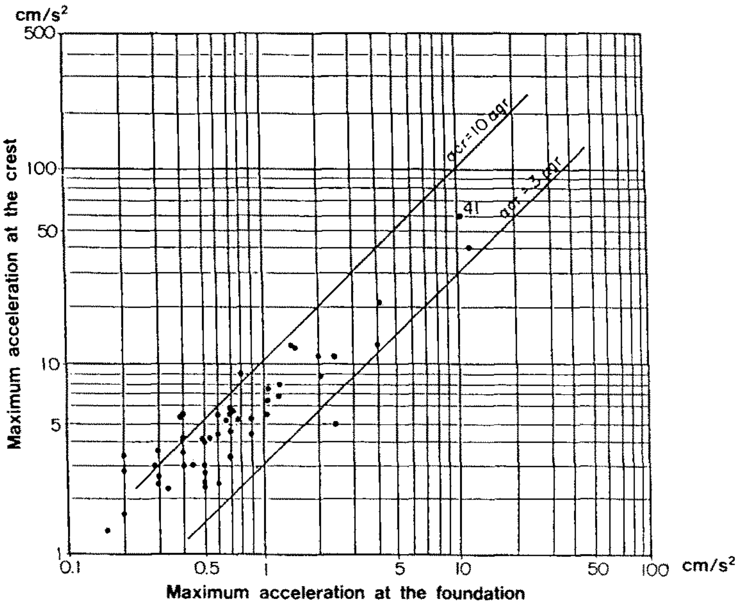


Fig 6-6-2 Amplification of Response

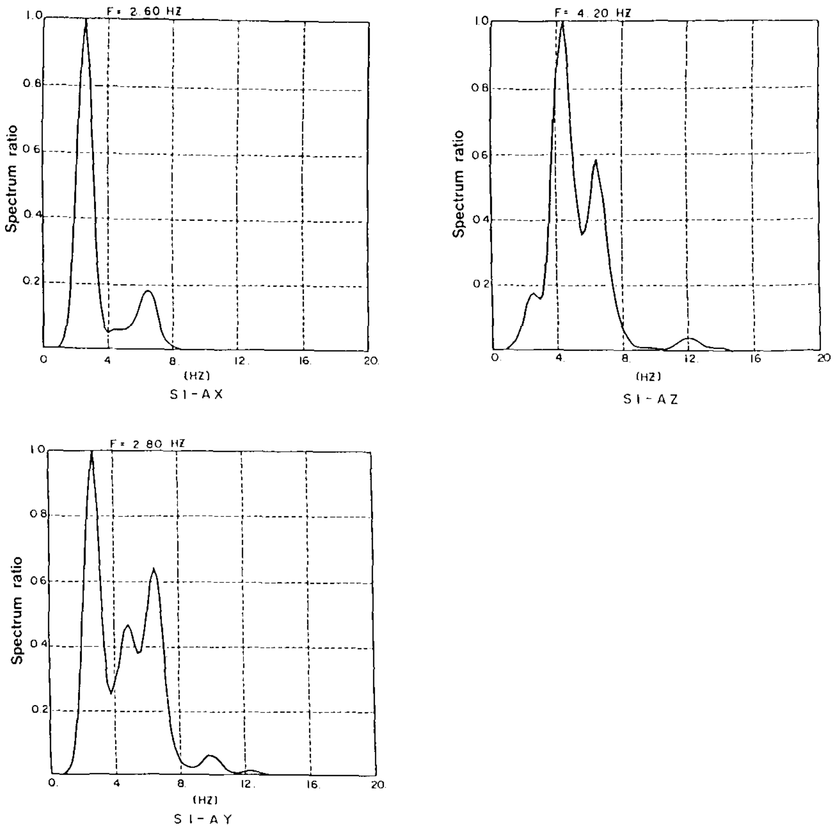


Fig 6-6-3 Power Spectrum

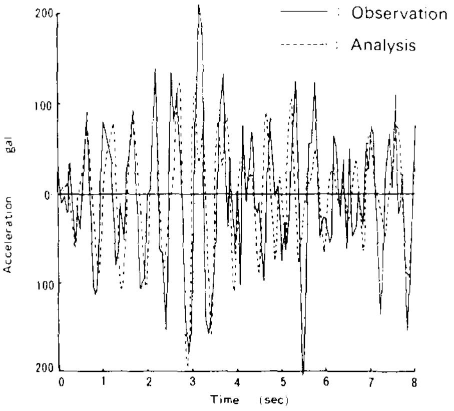


Fig 6-6-4 Seismic Motion at Crest
(Observed and Analysednal)

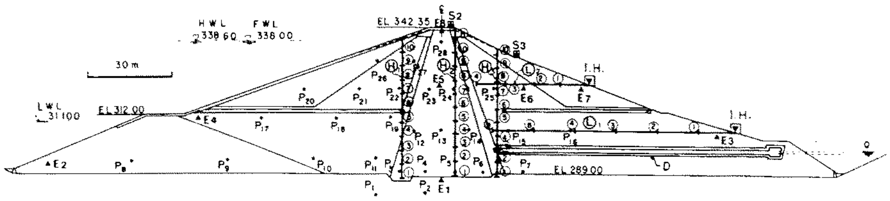


Fig 6-7-1 Fukada Dam

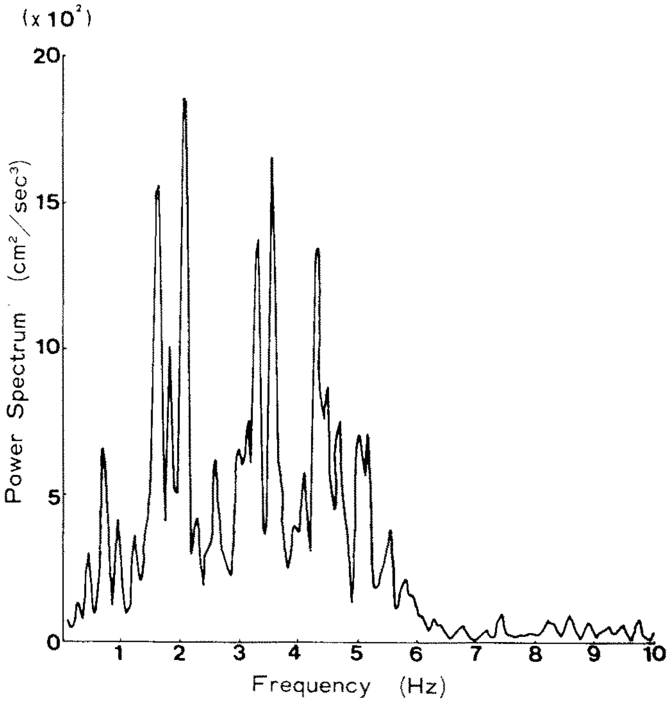


Fig 6-7-2 Power Spectrum of the Base Motion

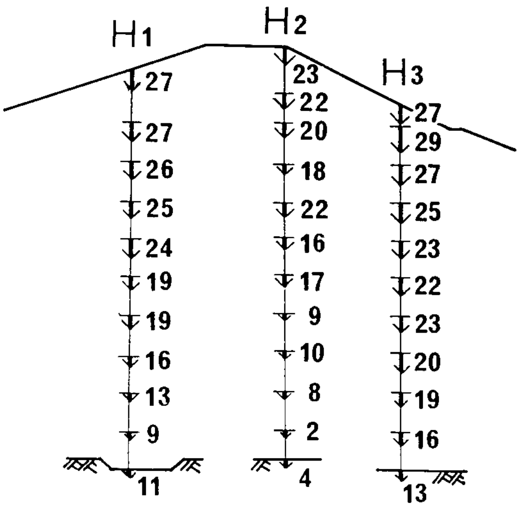


Fig 6-7-3 Settlement after Earthquake (mm)

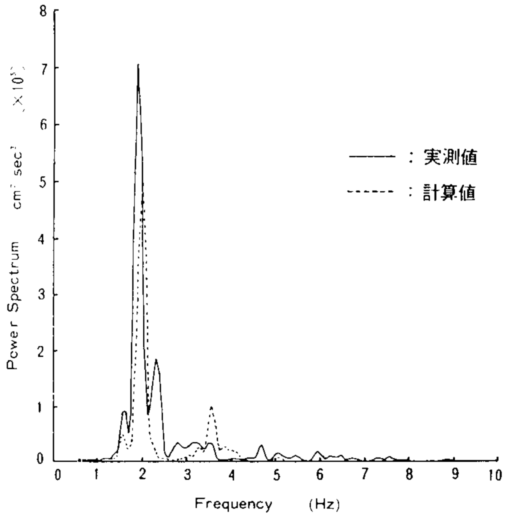


Fig 6-7-5 Power Spectrum at Crest

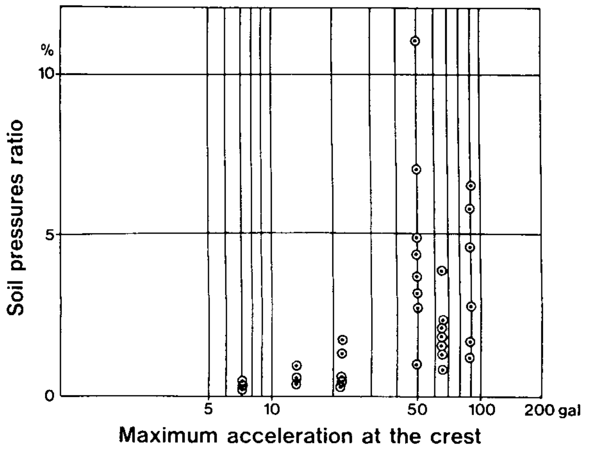


Fig 6-4-6 Soil Pressure Ratio

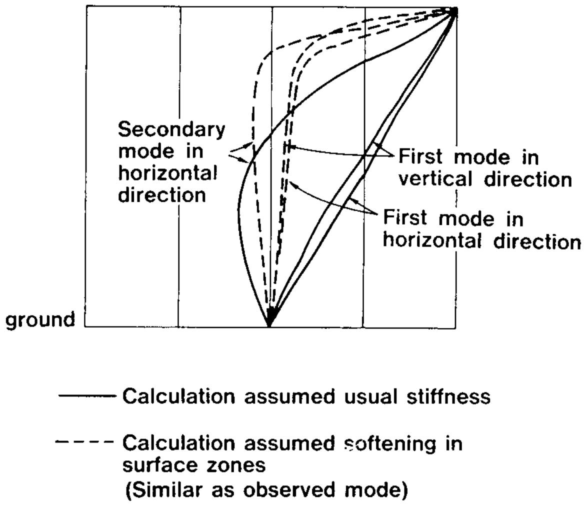


Fig 6-4-7 Vibration Modes

Appendix G
Annexe G

REPORT BY THE NORWEGIAN NATIONAL COMMITTEE

The Norwegian Regulations for Planning, Construction and Operation of Dams requires that provisions be made for monitoring the performance of dams but, except for measurements of seepage and deformation, the Regulations do not specify what is to be monitored or how long. The detailed design of the instrumentation program is left up to the designer but the proposed monitoring program is subject to approval by the regulating authorities.

This report summarizes current practice in Norway for monitoring embankment dams. Emphasis has been placed on methods and types of equipment used to instrument rockfill dams.

1 THE ROLE OF INSTRUMENTATION IN NORWEGIAN DAM PRACTICE

1.1 Background

In Norway more than 250 dams with a height of over 15 m have been built to date; approximately half of these are earth and rockfill dams. Although there are a large number of concrete gravity dams, buttress dams and arch dams in Norway, these are generally small in size and are seldom instrumented. For this reason this report is limited to a review of current practice for monitoring Norwegian embankment dams.

The increased emphasis on the construction of embankment dams for hydroelectric schemes in Norway after World War II has brought about a parallel growth in the use of instrumentation for monitoring the performance of these structures. However, the number of embankment dams that have been extensively instrumented is relatively small. Three factors that contribute to this situation are:

(a) The topographical conditions at most of the Norwegian dam sites are generally well suited for construction of embankment dams. The majority of the dams can be founded directly on bedrock of high quality, the valleys are rather small in width, and it is usually possible to find high quality moraine, gravel and rockfill for construction.

(b) The dams are similar in design. Of the total of 140 large embankment dams constructed to date, 95 of these are rockfill dams with a central impervious core of morainic material. Most of these dams are of comparable height and have been designed and constructed in a similar manner. Thus, once satisfactory performance has been verified for one or two of these dams, it has not been considered necessary to use extensive instrumentation schemes to reconfirm satisfactory operation on all subsequent dams of comparable height.

(c) The principal construction material is rockfill which is an extremely difficult media to instrument. Direct measurements of the insitu properties of rockfill or measurements of internal stresses in a rockfill embankment are almost impossible to make. Thus the performance of a rockfill embankment has to be evaluated primarily on the basis of deformation measurements alone.

1.2 Instrumentation philosophy

The Norwegian approach to dam instrumentation has been to concentrate instrumentation on dams that have an unusual problem or those that have design features which deviate significantly from existing dams, or those that are the first of a new class or type. These structures are then extensively instrumented, in particular if it is anticipated that a number of similar ones are to be built in the future. The objectives of these instrumentation programs are two-fold: to confirm that the new design is sound, that is, to verify that no unexpected conditions arise during construction and that the long-term behaviour is satisfactory and in accordance with predictions; and, to obtain sufficient detailed construction data and long-term performance data to enable extensive off-line analyses of predicted behaviour. Analyses of this kind can lead to improved computational models and methods which in turn may result in technical, economical or practical improvements in the design of dams in the future.

TABLE I
Instrumented Embankment Dams in Norway

Name of dam	Year completed	Maximum height m	Volume m^3	Type and number of instruments							
				Leakage measurements	Survey monuments	Inclinometer casings	Extensometers	Piezometers in embankment	Piezometers in foundation	Total stress	Temperature
Essand	1947	8						22			
Mosvatn	1953	26	115 000					7			
Strandevatn	1956	40	380 000					18			
Bordal	1959	42	300 000	3	41			33	11		16
Lille Manika	1964	15	125 000	1					11		
Hyttejuvet	1965	93	1 435 000	1	30			28		1	
Sonstevann	1966	45	502 000	1	30			6	19		
Vaslivatn	1967	25	70 000	1					8		
Kalvatn	1967	49	405 000	1	11			10		10	
Akersvann	1967	54	1 085 000	1				7		5	
Mandola	1969	27	114 000	3	17				8		
Muravatn	1968	77	100 000	1	54				9		6
Follsjo	1969	74	940 000	4	17			8			
Gråsjo Trial Dam	1969	12	–	1	9		6	7			
Lopet	1970	17	212 000	1					10		
Svartevann	1976	129	4 715 000	1	160	8	28	30		60	8
Nyhellern	1979	85	2 616 000	1	277	2	30	16			6
Innerdalen	1981	54.5	702 000	1	82			9			
Nerskogen	1981	55	1 470 000	6	138				27		
Vatnedalsvatn S	1983	60	900 000	2	76		13	12	3	27	4
Vatnedalsvatn M	1983	125	4 200 000	1	186	4	38	29		40	5
Oddatjorn	1986, 87	145	5 380 000	1	247		41	32	8		6
Storvassdamen	1987	90	9 700 000	3	284	12	30			10	

1.3 Scope of routine monitoring programs

As pointed out above, for the majority of the dams in Norway only a routine instrumentation program is implemented. Of the 150 or so embankment dams that have been built to date only 23 of these have what could be considered to be a non-routine monitoring program. TABLE I summarizes the scope of the monitoring programs for these 23 dams. For the other dams a routine monitoring program may include three basic types of measurements, namely:

- measurements of leakage to evaluate the long-term performance of the completed structure;
- measurement of deformations of the surface of the dam during construction and on a long-term basis; and in some case,
- measurements of pore water pressure in the core material to verify that the embankment is being constructed at a safe rate.

The first two types of measurements listed above are generally carried out on all high dams because they are required by the Norwegian Regulations, see Section 4. Whether pore pressures or other parameters are monitored or not, depends on details of the dam.

2 BASIC INSTRUMENTATION TECHNIQUES AND EQUIPMENT

The main objectives of this Section are to point out the specific measurements that are included in monitoring programs for embankment dams, and to describe the measurement techniques and equipment currently used in Norway. The use of this instrumentation in a monitoring program for a typical large dam is illustrated for the case of Svartevann Dam, a 129 m high dam with a central sloping core of moraine. Svartevann Dam is an example of a dam that was thoroughly instrumented because at the time it was built it differed significantly in size and concept from the existing dams in Norway.

The principal factors in selection of instruments for monitoring the performance of dams are robustness and proven long-term reliability. The majority of the remote reading instruments currently used in Norway are based on the principle of the vibrating-wire strain gauge and have their origin in instruments developed at the Norwegian Geotechnical Institute.

2.1 Measurement of leakage

Leakage data is undoubtedly the best indicator of the overall performance of a dam. The reason for this is that leakage is an integrated quantity and, thus, reflects the performance of the entire dam and not just the conditions at discrete instrumented points. The Norwegian Regulations require that leakage be monitored for all large dams.

Chemical analysis of leakage water is not undertaken unless an abnormal amount of leakage occurs.

2.1.1 Method of measurement

Leakage water is impounded downstream of the dam and diverted to a weir-station where V-notch weirs are used to measure the flow. The major problem in monitoring leakage is to be able to collect the water that seeps through the dam and/or enters drainage galleries or other forms of drainage control works. This is not easily done for all dams. In some cases considerable effort and cost may be required to construct berms and trenches needed to divert leakage water to one or more weir-station.

Level switches are used to provide independent alarm signals and to detect flooding of the weir-station.

In most instances leakage data is transmitted over telephone lines or via radio to a central monitoring station or control room.

2.1.2 Description of instruments

Hook-gauges or calibrated scales are provided for direct measurement of leakage. For automatic measurements the operating head on the V-notch weir is determined with vibrating-wire strain gauges that sense variations in the buoyancy force acting on a cylinder partly submerged in the stilling basin behind the weir plate, Fig. 1. Two water level sensing devices are included to provide complete redundancy because of the importance of the leakage measurements.

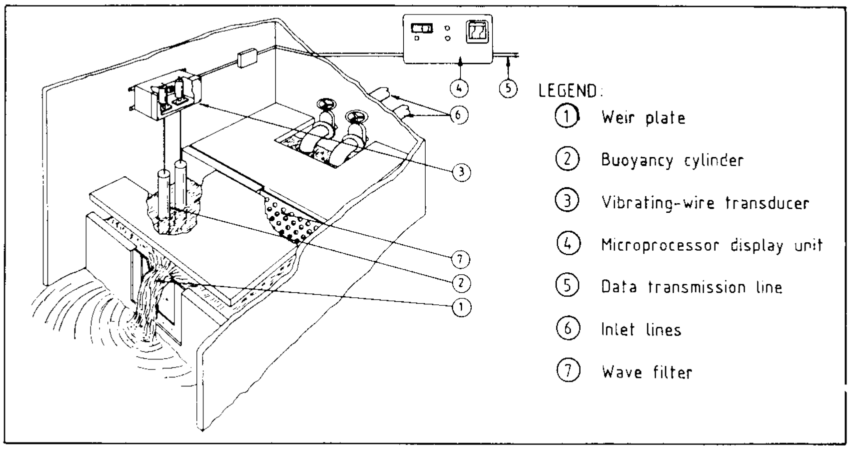


Fig. 1 Instrumentation system for continuous monitoring of leakage.

A microprocessor-based readout instrument converts the strain gauge signals to scaled discharge values in liters/sec. The instrument also provides alarm signals as well as analogue voltage and current signals or digital signals for driving a chart recorder or for data transmission.

2.1.3 Installation and measurement procedures

Since most Norwegian dams have a small crest length and are founded on good quality bedrock, leakage water can usually be collected and fed to a single weir-station. To do this a seepage barrier of moraine or concrete is constructed across the valley floor to form a permanent basin for impounding seepage water as shown in Fig. 2. The location of the barrier is, of course, dictated by the topography at the site. Whenever the topography permits, the barrier is located within the dam immediately downstream of the dam axis in order to minimize the influx of rain and snow melt water into the collection basin. This position is quite favourable in the case of a dam like Svartevann Dam because the collection basin is relatively well sheltered against inflow of precipitation and melt water by the overlying sloping core.

When feasible, the collection basin is divided into separate parts by suitable barriers such that seepage originating from different sections of the dam can be measured independently.

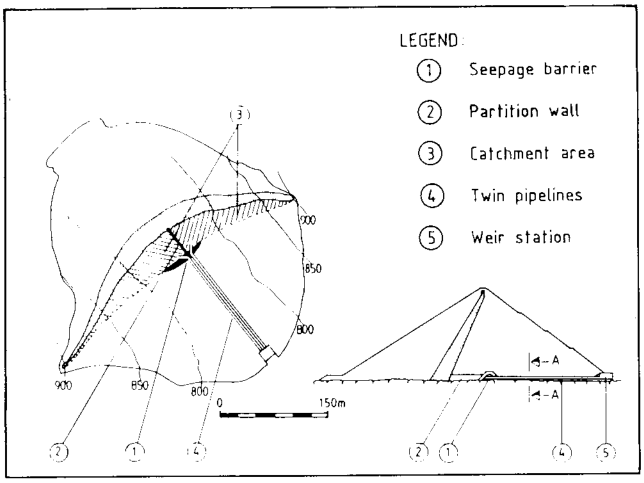


Fig. 2 Arrangement for measurement of leakage at Svartevann Dam.

2.1.4 Frequency of observations

The frequency of leakage measurements depends on the amount of observed leakage. It can vary from continuous readings to only a few observations per year if the leakage rate is very small.

2.2 Measurement of surface deformations

The Norwegian Regulations for dam construction recommends that surface deformations be measured for all large dams. Since surface deformation is in a sense an integrated quantity, measurements of this kind will also reflect the performance of the entire dam, just as leakage measurements do, provided that the number of points included in the survey is large enough to give a complete picture of the deformation pattern for the entire dam. Furthermore, if the performance of the dam is not as it should be, it may be possible to localize the source of the problem on the basis of anomalies or discontinuities in the measured pattern of deformations.

2.2.1 Method of measurement

Horizontal and vertical movements of a network of reference monuments on the slopes and crest of the dam are determined by triangulation or by a combination of angle and distance measurements from geodetic stations established near the dam. The grid of survey monuments and geodetic stations used at Svartevann Dam is shown in Fig. 3.

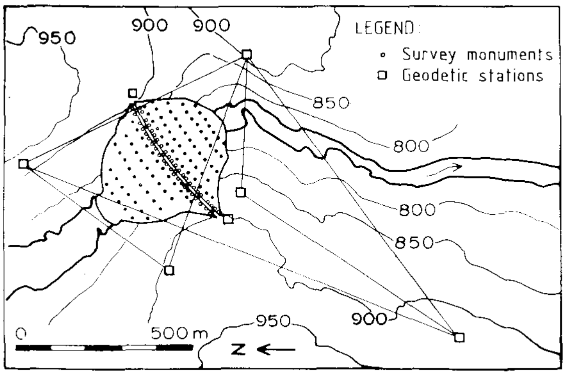


Fig. 3 Baselines and grid of survey monuments at Svartevann Dam.

2.2.2 Description of instruments

Standard survey targets are used as survey monuments and triangulation is done with precision theodolites. The distance to reference monuments, and the baselines between geodetic stations are measured with electronic distance measuring equipment. Settlements of reference plates along the crest of the dam are measured with precision levels.

2.2.3 Installation and measurement procedures

The sockets for the survey targets are grouted into holes drilled into selected rockfill blocks. Settlement reference plates are set along the crest of the dam at the elevation of the top of the impervious core.

The triangulation stations consist of a concrete pedestal fitted with a centering mount for the particular theolodite to be used for the measurements.

2.2.4 Frequency of measurements

The monuments are surveyed at key stages during construction and before and after the first two cycles of filling and emptying the reservoir. Afterwards the frequency of the measurements depends partly on the magnitude and rate of deformations observed. During operation of the dam the measurements are generally taken a minimum of once per year. The baseline distances are checked periodically by specialty surveying contractors.

2.3 Measurement of internal deformations with survey probes

Measurements of internal deformations are not mandatory in Norway. Whether these deformations are measured or not depends on details of the dam. Thus, the need has to be evaluated in each case.

Measurements of this kind are particularly important in cases where an appraisal of the performance of the dam depends on knowledge of differential settlements, horizontal displacements or relative movements of different materials or zones within the dam.

2.3.1 Method of measurement

Displacements within the dam are determined from the measured change in inclination and length of telescopic inclinometer casings installed in the dam. As shown in Fig. 4 for Svartevann Dam, these casings may be inclined, vertical or horizontal depending on the design of the dam and the type of measurements desired. The free ends of the casings used for displacement measurements are tied into the geodetic survey system so that absolute displacements can be determined.

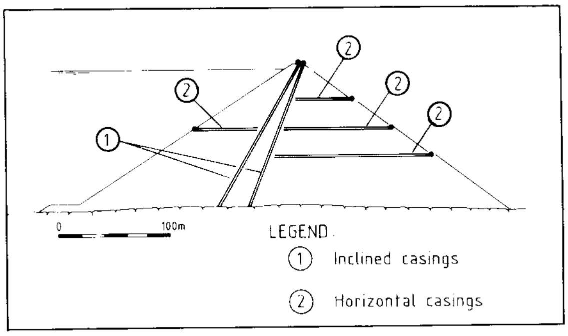


Fig. 4 Svartevann Dam. Central cross section. Locations of inclined and horizontal inclinometer casings.

Since it is not feasible to instrument an entire dam in this manner, the instrumentation is usually concentrated in one or more characteristic cross sections, or in a region where it is anticipated that a problem may develope. The exact locations of the instrumentation is often based on a finite element analyses of the dam.

Borehole inclinometers are used to measure changes in slope of the casing. This information is processed to obtain horizontal displacements for vertical or inclined casings. Whereas for a horizontal casing, settlement is derived from the slope measurements. Displacements along the longitudinal axis of casings are determined with a magnetic probe which utilizes a reed switch to detect the position of reference magnets attached at regular intervals to the telescopic casing.

2.3.2 Description of instruments and components

Heavy duty steel tubular casing sections with a cross section 100 mm by 100 mm and a wall thickness of 4 mm are generally used. These are joined together with loose-fitting telescopic joints. An installed casing resembles a chain with rigid links connected together in a way that permits a great deal of relative movement between links. Standard joints can telescope about 150 - 200 mm and allow for approximately 5 degrees rotation between two consecutive sections of casing. The wheel system on the inclinometer probe is designed to track along one side of the square casing.

The sensors in the inclinometer probes used to survey the casing are gravity-referenced servo-accelerometers. The inclinometers used to survey vertical and horizontal casings have the sensors mounted parallel and perpendicular to the longitudinal axis of the instrument respectively.

If displacements along the longitudinal axis of the casing are to be measured, rod magnets are mounted in milled slots in the casing. These magnets activate a reed switch in the survey instrument and provide a basis for measuring changes in distance between the reference magnets. The inclination sensor and the reed switch are usually combined in one probe in order to simplify the measurements.

Quick-connect aluminium rods are normally used to push the instrument into horizontal casings. Casings up to 150 meters in length have been surveyed in this manner.

2.3.3 Installation and measurement procedures

A "cut and cover" procedure is generally used for installing vertical and inclined casings. With this method, extension of the casings lags placement of fill by up to several meters. When a new section is to be added, an excavation is made through the overlying fill to expose the top of the buried casing; a new section is added; the top is capped; the excavation is backfilled and compacted; and placement of fill can continue unobstructed by the casing. Special care has to be taken in compacting the backfill in the excavation to insure that the compressibility of the recompacted material is the same as the unexcavated material.

2.3.4 Frequency of observations

Internal deformations are measured at key construction stages while the dam is being built and before and after the first two cycles of filling and emptying the reservoir. Afterwards the measurements are taken very infrequently unless there is some specific reason for continuing the observations.

2.4 Measurement of internal strain with extensometers

Extensometers or long-base strain meters are used to measure internal strains and deformations at locations where it is impossible or impractical to make such measurements using survey probes pulled or run through casings. Extensometers have been used, for example, to measure changes in width of impervious membranes in embankment dams, and to measure strains in regions of potential tensile stress or along the longitudinal axis of a dam.

2.4.1 Method of measurement

Remote reading vibrating-wire extensometers of the type shown in Fig. 5 are installed at locations where internal strains are to be measured.

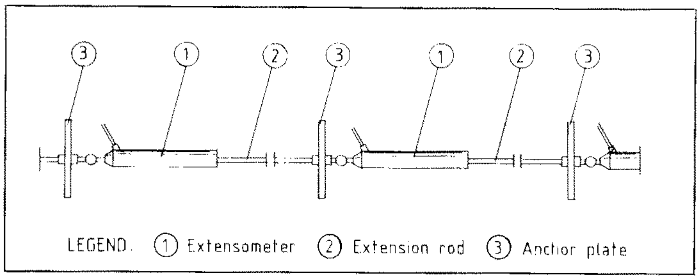


Fig. 5 Extensometer for measurement of internal strain.

2.4.2 Description of instruments and components

The extensometer is mounted in series between two anchor plates embedded in the fill material. The gauge length of the extensometer is regulated by adding the desired number of extension pipes between the anchor plates and the measuring unit.

Typical operating ranges vary from 0 - 20 mm for the extensometer used to measure change in thickness of a narrow asphaltic concrete core, to 0 - 200 mm for a typical 10 m long extensometer used to measure strain in a moraine core.

2.4.3 Installation and measurement procedures

Extensometers installed to measure strains along the longitudinal axis of the dam are normally located at the core-filter interface. These are linked together in 4 to 12 m long sections by universal joints, extension pipes and anchor plates to form continuous extensometer chains of varying length depending on the geometry of the dam. A plastic sleeve is placed over the extension pipes to reduce frictional forces on the pipes. Continuous extensometer chains up to 120 m in length have been installed using this procedure. The locations of the 5 strings of extensometers installed at Svartevann Dam are shown in Fig. 6. In all 28 extensometers were installed in the dam.

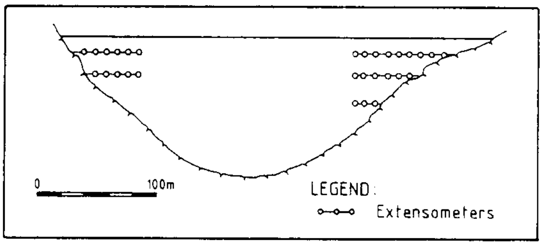


Fig. 6 Svartevann Dam. Longitudinal section. Locations of extensometer string.

2.4.4 Frequency of observations

Extensometers are usually read on a daily or weekly basis while the dam is being built and during the first two cycles of filling and emptying the reservoir. Afterwards the frequency of the measurements depends partly on the magnitude and rate of observed strains.

2.5 Measurement of pore water pressure

The Norwegian Regulations do not specifically require pore pressure measurements in embankment dams. The need for these measurements has to be evaluated in each case.

Pore pressure measurements are needed principally to verify that the stability of the dam is adequate. Pore pressure data can also be used to confirm the geometry of the flownet used to predict leakage rate. Measurements of pore pressure during construction are of particular interest because of the relatively short construction season and the desire of the contractor to place fill as quickly as possible without adversely affecting the stability of the dam.

2.5.1 Method of measurement

The four basic types of pore water pressure measuring instruments currently used in Norway for monitoring the behaviour of embankment dams are shown in Fig. 7. Two of these are hydraulic piezometers and two are vibrating-wire piezometers. The two on the left are for borehole installations; the other two are used primarily in embankments.

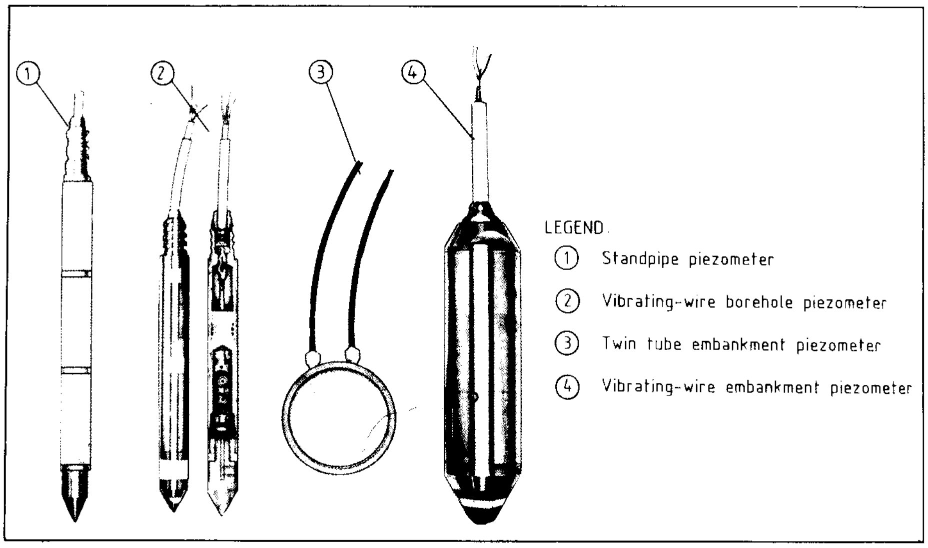


Fig. 7 Piezometers.

2.5.2 Description of instruments and components

The borehole piezometers are standard instruments that require no further description. The twin-tube piezometer has a diameter of approximately 100 mm. It can be fitted with a coarse filter stone or a high air-entry value filter, 6 mm thick with an air entry value of 210 kN. The nylon-polyethelyne tubing used with the piezometer has an OD of 6.4 mm and an ID of 2.7 mm.

The vibrating-wire piezometer embankment piezometer used in embankments has a high air-entry filter formed by casting an Aerox VI Cellaton filter in a conical-shaped epoxy body which is threaded into the piezometer. One special feature of this piezometer is that the body of the piezometer is purposely made unusually thick to avoid distortion of the sensing membrane which might occur if the earth pressure surrounding the instrument is very large as can be the case for a high dam.

2.5.3 Installation and measurement procedures

Borehole installations require that an adequate seal be made around the cable, tubes or pipes connected to the piezometer. Current practice involves seals made of bentonite or bentonite-cement mixtures and chemicals. Mechanical or hydraulic packers are sometimes used in cased boreholes or for borehole installations in rock. Procedures have been developed for installing and sealing more than one instrument in a borehole.

When fitted with a high air entry filter the vibrating-wire piezometer is normally saturated prior to shipment to the site. It is installed by first making a "socket" in the fill with a mandrel having the same dimensions as the filter. Once the socket has been formed, the piezometer is pressed into the socket to insure good contact between the filter and soil. The locations of the piezometers installed in the core of Svartevann Dam are shown in Fig. 8. In all 30 piezometers were installed in the dam.

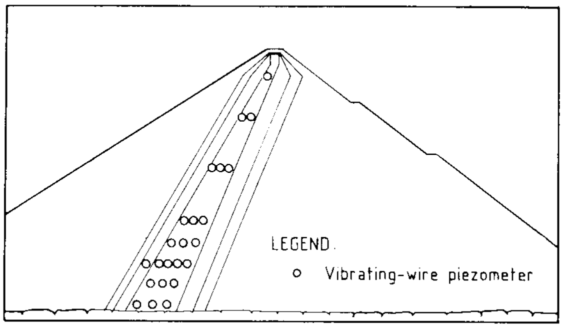


Fig. 8 Central cross section Svartevann Dam. Locations of pore pressure piezometers.

2.6 Measurement of total earth pressure

Total stresses have been measured in Norwegian dams primarily to study the potential development of cracks in high dams with relatively thin impervious cores.

Measurement of total stress within an embankment is not done on a routine basis because of the great difficulty in making such measurements. So far only three large dams have been thoroughly instrumented for this purpose, namely, Svartevann Dam and the Vatnedalsvatn Main Dam and Secondary Dam.

2.6.1 Method of measurement

Total stress is measured directly by means of earth pressure transducers embedded in the fill and oriented to measure stresses in a specific direction. Single instruments are used or if the principal stresses are of interest, the instruments are installed in rosette groups. The locations of the instruments in the central cross section of Svartevann Dam are shown in Fig. 9.

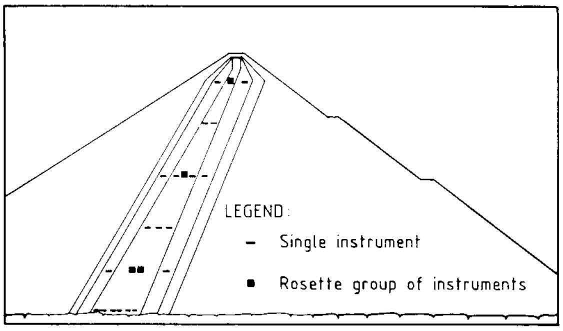


Fig. 9 Central cross section Svartevann Dam. Locations of earth pressure cells.

2.6.2 Description of instruments and components

Fig. 10 shows three types of total earth pressure sensors have been used to monitor internal stresses in Norwegian embankment dams. The most commonly used instrument in the morainic core material is a vibrating-wire membrane type pressure transducer. In order to minimize disturbances to the stress field when the instrument is embedded in the dam, the instrument is flush mounted, front and back, in the centre of a flat plate having the same thickness as the instrument, Fig. 10B. The dimensions of the plate are such that thickness to plate size ratio is approximately 1 to 15.

The second type of instrument consists of a relatively thin, circular shaped, oil-filled hydraulic capsule which is connected by a short length of hydraulic tubing to a vibrating-wire transducer, Fig. 10A. The advantage of this type of instrument is that it is relatively easy to increase the diameter of the capsule to obtain a more favourable thickness to diameter ratio or to satisfy size requirements for measurements in coarse grained material. The capsules used in moraine fill material have a diameter of 300 mm whereas those used in the filter zone are 600 mm in diameter.

The third type of total pressure sensor used is the well known Gløtzel cell, Fig. 10C.

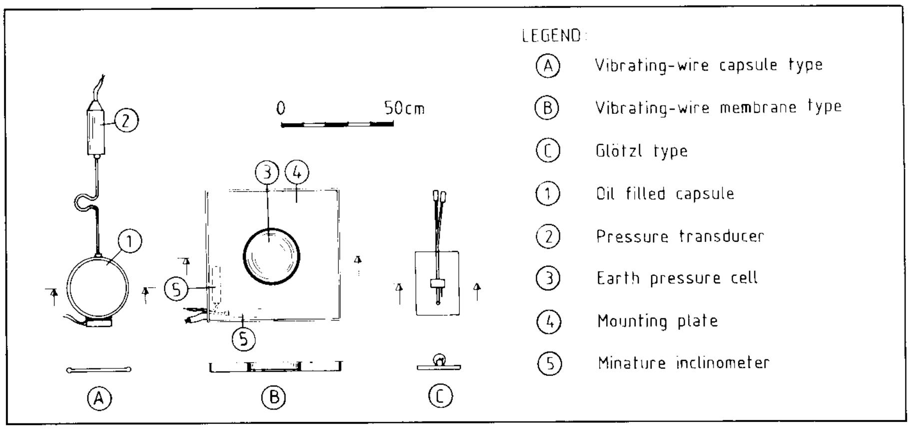


Fig. 10 Instruments for measurement of total pressure.

2.6.3 Installation and measurement procedures

To avoid damage to the pressure sensors due to heavy construction traffic, the instruments are installed by a "cut and cover" method. When the elevation of the fill is approximately one metre over a proposed sensor installation, part of the fill material is excavated to form a wide-bottomed excavation with flat sloping sides in all directions. The sensors are then installed in the bottom of the excavation. The size of the excavation depends on the number of instruments to be installed, but a significant amount of earthwork may be involved. For example, for one of the lower instrumented sections at Svartevann Dam the volume excavated was approximately 200 cubic metres.

The earth pressure sensors that are oriented horizontally are placed on carefully prepared smooth surfaces, then backfilled and compacted by hand. The amount of compaction is based primarily on judgment. A mandrel is used to shape a socket for the capsule type pressure sensors. When installing instruments in a rosette pattern, vertical or inclined sensors are hand-held in the proper direction while backfill is placed and compacted.

Although the pressure sensors are carefully aligned during placement, there can be no guarantee that they remain in this position during compaction and subsequent placement of overlying fill. Since it is important to know the actual orientation of the sensors, miniature inclinometers are attached to the pressure sensors to determine their true orientation.

3 DATA ACQUISITION EQUIPMENT AND PROCEDURES

Data acquisition equipment and methods vary from project to project. On smaller projects with a limited number of instruments, data are often recorded manually with the aid of simple portable instruments. On larger projects and in particular for projects in very remote areas, data are recorded automatically by small microprocessor-based data loggers. Recording media are generally magnetic tape cartridges and line printers. Limited amounts of data are also stored in solid state memory devices which can be accessed upon request locally or remotely over telephone lines.

Seepage data are dealt with separately. Seepage is recorded continuously in the vicinity of the weir-station on strip-chart recorders. In addition, the data is transmitted to the nearest power station control room. In some parts of the country the data is relayed to a central station which monitors the seepage for all dams in the area.

The Norwegian Regulations do not specify how long measurements are to be continued. During construction it is common to take daily or weekly readings of electrical instruments. Inclinometer and geodetic surveys are generally taken before and after each key construction stage or activity. In practice the duration of the monitoring programs normally includes the first two cycles of reservoir filling and drawdown. Afterwards, only leakage and surface deformations are measured systematically on a long-term basis. The frequency of leakage measurements depends on the amount of observed leakage. It can vary from continuous readings to only a few observations a year if the leakage rate is very small. If internal deformations, pore pressures and total stresses in the embankment are included in the monitoring program, these are measured very infrequently once the reservoir has been filled once or twice unless the measurements indicate a need for more frequent observations.

Data reduction is done automatically in the office or control room and not generally at the dam site. Standard plotting formats for graphical presentation of results are becoming common place in Norway, and this is contributing to a more efficient analysis of the data.

4 REGULATORY REQUIREMENTS FOR INSTRUMENTATION OF DAMS

Dams in Norway are owned and operated by either private, semi-private or national companies. The control of all water power resources, however, is under complete state control through the Norwegian Water Resources and Energy Administration (NVE). The State Power Board is responsible for the design, construction and operation of the state owned systems. Approximately 30 per cent of the total hydroelectric generating capacity is designed, constructed and operated by the State.

Since 1981 all dam building in Norway has had to be carried out in accordance with the official "Norwegian Regulations for Planning, Construction and Operations of Dams" which sets requirements for all dams. The federal agency that is responsible for the supervision and regulation of Norwegian dams is the Directorate of Water Resources - a directorate within NVE. Within this directorate the supervision of dams is performed by a special division, the Technical Supervision Division, known as VVT.

In brief, the Regulations provide for systematic inspection and monitoring programs for dams, and reporting of control and observation data to VVT. Responsibility for the technical supervision work must be delegated to named persons since VVT has the authority to set requirements for the technical qualifications of personnel responsible for control and maintenance of dams. VVT has its own inspectors who undertake independent inspections and who have access to the Owner's records.

The Norwegian requirements regarding monitoring programs for dams are not detailed or specific with respect to defining the scope of the monitoring program or the length of time that measurements are to be continued. They do require, however, that plans are made in advance for providing instrumentation of the amount and type that is deemed necessary to monitor the performance of the dam in question. The responsibility for detailing the monitoring program falls on the owner and/or the designer of the dam. VVT of course must approve the instrumentation scheme that is proposed.

Although the requirements are not specific regarding the overall monitoring program, measurements of leakage and surface deformations are strongly recommended for all large dams. These two types of measurements thus form the basis for all the monitoring programs carried out in Norway.

The instrumentation requirements discussed so far deal with monitoring programs aimed primarily at documenting the performance of the dam during construction and after it is completed. Guidelines for a second type of instrumentation - for a public warning system - were set forth by Royal decree in 1965. At present the responsibility for establishing a warning system is divided between two different ministries, namely: the Royal Ministry of Petroleum and Energy, and the Royal Ministry of Justice and Police. According to the 1965 guidelines the minimum instrumentation for a public warning system should include at least the following three things:

- at least one signal wire attached to the structure;
- a suitable device for continuous measurement of leakage; and,
- at least one water level switch located downstream near the dam.

Appendix H
Annexe H

REPORT BY THE PORTUGUESE NATIONAL COMMITTEE

The monitoring of dams and their foundations began in Portugal at Santa Luzia dam, an arch dam, 76 m in height, constructed in 1942. Nowadays these activities are developed for the most of the 80 existing Portuguese large dams whose distribution by structural types is : 29 gravity dams; 22 earth dams; 11 arch dams; 5 arch gravity dams and 5 rockfill dams; 2 buttress dams; 2 composite buttress and earth dams; 1 multiple arch dam; 1 composite multiple arch and earth dam; 1 composite gravity and earth dam; 1 composite earth and rockfill dam. Monitoring of the most of these dams, their foundations and appurtenant works has been carried out taking into account their particular characteristics (age, maintenance condition, structural solution, etc.) and has been developed according to rules essentially decurrent of the followed practice. Despite the satisfactory results so far obtained, the convenience, felt since a long time ago, of the establishment of some general guidelines framing the safety control activities has justified the constitution of a Committee to prepare Dams Safety Regulations. The main aspects of the organization recommended by these Regulations will be briefly presented in this text.

The physical quantities, the corresponding instruments and the related experience and also the main characteristics of the monitoring schemes installed are succinctly reported.

The frequency of measurements usually adopted, the methods followed in the analysis of results and the present state of automation of the monitoring activities will be also reported.

1. ORGANIZATION OF MONITORING ACTIVITIES

The Dams Safety Regulations apply to dams that present great or significant human or economic hazards. All dams higher than 15 m (or lower dams, with reservoir capacity greater than 100 000 m^3, or having special foundations, or any other particularity justifying that level of hazard) are considered within the scope of these Regulations. New dams, even not having these characteristics, can also be submitted to these Regulations whenever special circumstances arise, by decision of the entity who approves the corresponding designs.

In what concerns public entities, the safety control is attributed to an official entity named, for Regulations purposes, Authority, who will have, in the execution of the corresponding activities, the collaboration of LNEC (National Laboratory of Civil Engineering) and of SNPC (National Service of Civil Defense) and also the assistance of the Committee on Dams Safety — a new entity created by these Regulations.

The safety control begins in the design phase and is to be developed through the full life of the dam, namely during construction, first filling of the reservoir, operation, and abandonment and demolition.

The Regulations define the competences of the public entities and the obligations of the owners. The Authority will : promote the participation of LNEC; approve the plans of monitoring and of the first filling of the reservoir; define, in collaboration with SNPC, the cases justifying the emergence planning and the implementation of warning systems; control the first filling of the reservoir; and, appreciate data records and the dams behaviour reports.

The competence of LNEC, when the Authority calls for it, refers essentially to : the preparation or the revision of the plans of monitoring and of the first filling; the implementation of the monitoring data storage and the use of it in order to have an updated knowledge of the dams behaviour; the continuous following of the dams behaviour; the preparation of expertise reports, during the first filling and during the first period of normal operation (as defined in the monitoring plan), as well as of a final report about the precedent behaviour; the appreciation of reports presented by others in the subsequent period of operation or the preparation of these reports; the inspection and the preparation of expertise reports following exceptional occurrences or anomalous situations.

The owners must : promote the preparation of the plans of monitoring and of the first filling and their submission to the Authority; promote the installation of the monitoring scheme; implement the control during the first filling; promote the monitoring of behaviour during the normal operation. The costs with the safety control and with other studies considered as indispensable by the Authority will be supported by the owner.

Special importance is given in the Regulations to monitoring and first filling plans whose specifications follow.

According to the Regulations, the design documents must include a general proposal of the monitoring scheme, which should indicate and justify in such detail as considered convenient by the designer, the physical quantities to be monitored, taking into account the hazard scenarios envisaged in the design. Following the design approval, the monitoring plan must be drawn up as soon as possible, fairly before the beginning of the construction phase. The most important aspects of the plan must integrate the construction specifications thus allowing a suitable coordination of the monitoring activities with the construction works.

The monitoring plan has to be based on the corresponding proposal and be implemented, at least in its final phase, with the collaboration of the different entities involved in the structural safety control. This plan must consider the hazard involved in the construction and operation of the dam and will contain indications about : *i)* visual inspections (frequency of visits, types of inspections and qualifications of corresponding agents, main aspects to be observed and presentation of reports); *ii)* installation and operation of the monitoring scheme (physical quantities to assess actions, structural properties and structural responses; specifications of instruments and accessories and of their installation and use; frequency of measurements during construction, first filling and operation phases and their adjustment in case of rapid variation of actions or of exceptional occurrences; methods of data collection and processing and communication procedures to follow in case of detection of anomalous behaviour; qualification of the agents charged of the installation and operation of the monitoring scheme); and *iii)* methods recommended for behaviour analysis and safety evaluation of the works (behaviour models to use considering the main hazard scenarios and reports to be prepared).

The Regulations points to the need of updating the monitoring plan when justified, which is compulsory after construction, first filling, first five years and first twenty years of operation.

The first filling is the loading test of the work and is the most critical phase from the point of view of the risk involved. In fact, the probability of rupture (based on statistical analysis of past cases) times the costs of damages it will cause during this phase, reaches greater values than those corresponding to the other phases. Accordingly the Regulations establish that an approach of the first filling plan must be presented with the design. Afterwards, a plan must be prepared sufficiently ahead of the beginning of the first filling, also for the revision of the design hypothesis and the assessment of the efficacy of the monitoring scheme (as regards the dam behaviour analysis during the operation phase). That plan must contain indications about : *i)* continuous visual inspection; *ii)* physical quantities to be monitored in order to assure quick safety control; *iii)* frequency of data collection taking into account the filling programme; *iv)* reservoir levels to be maintained during a certain period in which a set of observations must be made to allow, following an inspection visit and the analysis of the data collected, the assessment of the safety condition of the work; *v)* behaviour models to support the safety evaluation.

Besides these subjects, the Regulations define the safety control activities to be developed during the previously mentioned phases of the dams life. Finally, they establish that, for the existing dams and in a period of five years after they were put into force, adaption to their specifications must be made.

2. PHYSICAL QUANTITIES AND INSTRUMENTS

2.1. Concrete dams

The physical quantities monitored in Portuguese concrete dams are : reservoir levels, air and water temperatures, and when justified, ground motions, in what concerns external actions; and, in what concerns structural effects, displacements, rotations, joint and crack movements, strains and stresses, temperatures inside concrete, uplifts and seepage, and for dynamic aspects, displacements, velocities and accelerations.

The methods used for the measurement of displacements are : *i)* geodetic methods, namely triangulation, precision traverses and precision levelling; *ii)* direct or inverted plumb-lines; *iii)* borehole extensometers.

Triangulation methods are used in almost all dams. In fact, after the occurrence of some problems concerning the reliability of data, specially when a long period of time has passed from the initial measurements, studies of network conformation (assuring the more adequate positions of the fixed references — from the geometric and the geologic points of view and also of targets — from the structural and also the geometrical points of view), and the improvements of instruments (distanciometers and electronic theodolites) have prompted a new interest for these methods. Despite the difficulties related to the frequency of measurements and to costs involved (need of a specialized crew, expensive equipment and time), the fact that these methods are now much less time-consuming and that the corresponding information is reliable, leads to foresee a still wider use in the future.

After a relatively long period in which they were not applied, precision traverses of inspection galleries are nowadays considered as a useful method to determine relative or absolute displacements of points located in these galleries. Connected with external references (or with internal ones fixed into the rockmass far enough from the influence of the dam) or with plumb-lines (allowing to obtain absolute displacements) or even without any connection (then giving relative displacements), the precision traverses act as a complement of the displacements pattern obtained by other methods.

Precision levelling is widely used as it is a simpler method than the triangulation one and gives accurate results.

Plumb-lines, whenever possible inverted ones (despite the rigid specifications and costs of foundation drilling techniques), are in generalized use. Since frequent measurements are easily and accurately done with a movable optical coordimeter (calling only for local crews) and future measurement automation will be easy their wide use is justifiable as well as the increasing trend to their installation (in future or even in existing dams).

Rotations were usually determined by detachable clinometers. However, the use of these instruments is nowadays very limited; in fact, despite the high precision attributed to the device measurements, errors were very frequent and made the data analysis difficult. Rotations have also been measured and continuously recorded by means of photoclinographs. Another type of clinometer (of electric resistance type) has recently been used, creating good conditions to a new trend of rotations measurement.

Joint movements are measured by means of electric resistance jointmeters (inside the concrete mass or externally in a special installation), or by deformeters. In the first dams also vibrating wire strain gauges were used. However, only the former have been applied since then. These measurements are widely made, specially using deformeters (due to their low cost and easy installation and operation and to the accuracy of the corresponding results). By using deformeters, the opening and sliding movements of adjacent blocks can be easily measured.

Some difficulties were felt with the first used vibrating wire strainmeters which, despite some attempts to make corrections, have conducted to their abandonment in favour of the electric resistance strainmeters of Carlson type, which in general allow good operation and give adequate results. In fact, more than thirty years of experience shows that the percentage of defective apparatus is comparatively small and readings are reliable in most cases. Moreover, in more recent dams, the improvement of installation techniques, namely by adopting great care in what concerns vibrations of the concrete surrounding the instruments, protection of cables specially during construction (in the lifts and in the transition zones to the tubes connecting to the reading stations), protection with concrete of these tubes and protection of the external connections, etc., have conducted to good results in almost all the installed apparatus, which are functioning very well after several years.

Strainmeters are placed in groups of 9, 5 or 2. These schemes allow not only to obtain more than the minimum data necessary to calculate the corresponding state of stress but also to check the corresponding results. Near each group of strainmeters a device (no-stress strainmeter) is allways placed allowing us to measure the free volume variations of the concrete, either autogeneous or induced by thermohygrometric variations.

Beyond these instruments, another strainmeter was developed at LNEC to be installed in foundation rock. It has a gauge length of 2 m and its measuring element is a Carlson type jointmeter. The number mounted at each point depends on the state of stress expected. As a rule, groups of 5 or 7 have been placed, enabling us to measure shear stresses along directions in which maximum values are anticipated. Where special geologic features (such as faults or joints) exist, instruments were placed so as to detect the effect of those local discontinuities. Despite the satisfactory results obtained, they have not been installed in the recent dams.

Other devices were developed at LNEC to allow in situ tests of the deformability characteristic of concrete under sudden or sustained loads. These devices, called creep cells, are of two types, one for testing screened concrete and other for testing full-mixed concrete. The good results obtained until now and the importance given to the knowledge of *in situ* concrete properties (a research program including the study of these problems is now in course at LNEC), conducted to more intensive use of these devices.

Stresses can be computed from measured strains. Variation of applied stresses between two close dates can be obtained by accounting for the average modulus of elasticity in the interval; for greater intervals the anticipated evolution of concrete viscoelasticity or the information given by the creep cells must be considered.

Other instruments and methods to determine stresses have also been used, namely stressmeters and compensation and relief methods.

In what concerns stressmeters, after the use of other apparatus the Carlson type stressmeters have been adopted. The most recent analyses of their results have proved that they are sufficiently reliable, provided the instruments are adequately installed, which has been satisfactorily achieved in the majority of the existing schemes. So, they are being included in recent dams having in view also research purposes.

In some ancient dams stress measurements by compensation or relief methods have been made as a contribution to the behaviour analyses. The relief technique carried out by LNEC uses a borehole device of its own make, commonly referred to as stress tensor gauge or more recently, after some improvements, stress tensor tube (STT).

Stress evaluation in the surface neighbourhood, by the compensation method, by means of flat jacks, using instruments and techniques developed at LNEC, has given satisfactory results. This method, also known as small flat jack method (SFJ), uses the principle of the recovering of deformations. This technique also makes it possible to determine the elasticity modulus of the volume of the material involved in the test.

Temperatures are quantities measured in almost all the large Portuguese concrete dams. In the first dams built and in a few more, thermocouples were installed. However, in most existing dams only resistance apparatus have been used.

As all the electric resistance instruments supply local temperatures, the distribution of thermometers inside the dam body must take into account that fact in order to optimize the information about the thermal field of the dam.

Water and air temperatures are measured in the immediate vicinity of the concrete dam (fixing thermometers at upstream and downstream surfaces).

Uplifts and seepage are quantities measured in almost all large dams.

In what concerns dynamic quantities, displacements, velocities and accelerations have been measured with portable equipment in some Portuguese dams during blasting in the dam vicinity, occurrence of vibrations due to water discharges or operation of turbines or execution of forced vibration tests; in these tests the vibration has been induced by a mechanic vibrator and the structural response collected by means of movable velocity transducers. Only in Aguieira dam (a multiple arch dam, 89 m in height, constructed in 1981) a permanent equipment was installed (macrosismographs) at several points conveniently distributed (allowing to collect data during the occurrence of a possible significant ground motion).

2.2. Fill dams

The physical quantities usually monitored in Portuguese fill dams are : reservoir levels, in what concerns characterization of external actions (up to now no instruments to observe dynamic phenomena have been installed); and, internal and external displacements, pore pressures, total pressures and flows, in what concerns structural effects.

The methods for measuring displacements are : *i)* triangulation methods and precision levelling; *ii)* USBR cross-arms; *iii)* and slope indicators. In what concerns internal displacements, some special devices are now being developed to measure them along horizontal planes.

The experience with triangulation up to 1985 was to use easier methods for fill dams than for concrete dams on account of the different magnitude of displacements usually observed and the accuracy considered adequate. So, the requirements for the installation, methods and techniques involved in fill dams were not so exacting. However, for two recent dams special networks were developed in order to : *i)* carefully measure displacements of some points during the last phase of the construction, and to control the dams behaviour, in particular by measuring displacements, during the first filling of the reservoir; *ii)* obtain a reference observation, with a high reliability level, allowing to check abnormal displacements, if they are indicated by the intermediate, less exacting triangulations. So, special pillars has been used (similar to those used in concrete dams) as well as survey monuments carefully installed, integrating a network whose design, operating techniques and programs allow to minimize errors. For the intermediate observations adaptations have been introduced in the methods and techniques in order to reduce the time consumed, by facilitating the process without appreciable loss of accuracy.

Pore pressures are measured by means of hydraulic piezometers or pore pressure cells. The effective life of these cells is very limited (at most a few years).

The experience with Maihak cells shows that their average life is between six and eigth years.

Flows corresponding to individual drains or to the water passing through a certain zone are collected in standard vessels or in V-notch devices.

In a very small number of fill dams total pressure cells have been installed (of Glotzl type — hydraulic cells, and of Maihak type — diaphragm cells). Despite the difficulties involved in the installation of these instruments, good results have been obtained after introducing some corrections connected with the different deformability of the cells and the involving soil. So the continuity of their use in future dams is recommended. However, to avoid loss of information caused by possible damage of one of the instruments, clusters provided with superabundant apparatus will be installed.

3. MONITORING SCHEMES

The monitoring scheme of a certain dam, considered as the whole of the instruments installed in it is planned, as already said, in order to cover the different phases of the dam's life. Its composition depends not only on its type (concrete dams-arch, buttress and gravity; or fill dams-homogeneous, zoned and rockfill dams with upstream impervious face), its dimensions (height, crest length, reservoir volume, etc.) or other general characteristics (local and regional seismicity, type of foundation, downstream installations, etc.), but also on other specific conditions hardly repeated in other cases. However, there are some aspects that are common to all types of dams, such as the following ones.

In what concerns the construction phase, although indispensable to guarantee the safety of the different structures built along the time, it is not usual to establish in the monitoring plan a program specifically oriented to control their safety during this phase, excepting for visual inspection. However, the information obtained must achieve some important goals such as those mentioned afterwards.

The first filling of the reservoir may also influence the monitoring scheme. In fact, the need of a rapid assessment of the dam safety calls for the use of adequate instruments specifically giving information about the evolution of the quantities concerned with that safety with enough accuracy. Some other aspects of the monitoring schemes are specific to the dam's material (concrete or fill dams) or to the dam's structural types. Those aspects will be presented hereinafter.

3.1. Concrete dams

In what concerns the construction phase, thermometers (or other electric resistance instruments), rockmeters, creep cells and embedded strainmeters and stressmeters may supply very useful data. Thermometers give concrete temperatures with enough accuracy which allows the possibly to correct construction procedures, namely lifts height, concreting intervals and artificial cooling. Rockmeters, placed in due time under the concrete blocks, allow to assess the foundation deformability characteristics during the installation of the corresponding dead weight. Creep cells placed inside concrete inform about the evolution of the deformability of concrete, and supply data to determine the stresses from the strainmeter results. Strainmeters and stressmeters supply particularly important data in what concerns the reference state of stress of the dam-foundation structural complex obtained at the end of the construction.

In the first filling of the reservoir, besides the data concerned with external actions, the quantities specially related to safety are, in what concerns the body of the dam, horizontal displacements (mainly by means of plumb-lines and, at certain reservoir levels, also by geodetic methods), vertical displacements (by means of precision levelling and rockmeters) and movement of joints (especially by means of deformeters) and, in what concerns the dam foundation, displacements (by means of rockmeters), seepage and uplifts.

In the operation phase the quantities specially related to safety are, in general, also those previously mentioned.

Not only due to the above mentioned interest in the construction phase but also due to their contribution to a better assessment of the dam safety by means of a more accurate analysis, measurements of concrete temperatures, strains and stresses and, less frequently, rotations, are made in almost all Portuguese concrete dams.

Following these general aspects some others, specific to each structural type considered, will be presented.

3.1.1. Arch dams

Regarding external actions also ground motions ought to be monitored, when justified. However, as already said, no Portuguese arch dam has so far been permanently instrumented to achieve this goal. Nevertheless studies have been performed in order to install the necessary devices in existing and in future arch dams.

In what concerns planimetric displacements measured by triangulation, the targets are distributed over the body of the dam in order to obtain a good representation of its global movement (Fig. 1). They are installed along arches (usually at two levels, one near the crest, and other at medium height, or even at more levels when justified by the dam height) and along cantilevers (one along the main cantilever, or three or more distributed in order to cover the downstream part of the dam's body). Besides this, special attention is paid to the points near the foundation despite the usual difficulty in measuring them with enough accuracy.

Precision traverses, after a long period in which they have not applied as already said, were recently used again.

Altimetric displacements are usually measured by precision levelling of points located at dam crest and when feasible, also at inspection galleries and downstream surroundings. Absolute vertical displacements inside horizontal galleries are sometimes difficult to obtain due to the inexistence of fixed points in the vicinity, with which adequate connection might be established. However, some arrangements have been made, namely the connection between galleries by means of invar wires and the connection with rockmeters anchored to deep points installed inside galleries near the abutments.

Planimetric displacements by plumb-lines are measured in almost all the large Portuguese arch dams (Fig. 1). Their installation is usually coordinated with the choice of the positions of the downstream targets in order to check the displacements obtained at the same points by different methods. Beyond the displacements of the body of the dam particular importance has, in recent years, been given to the measurement of foundation displacements, in order to collect information about the mechanic behaviour of the dam foundation. According to main aims, borehole extensometers may be used, isolated or in groups, for instance in the three following types of installations : schemes of multiple borehole extensometers hole-fans, in order to obtain in addition to the absolute displacements of the intermediate anchored points and of the surface point (provided the deeper point is effectively fixed), also the rotation of the correspondent section (Fig. 1); schemes of simple or multiple borehole extensometers crossing significant foundation cracks or faults where movements affecting the dam behaviour can occur; schemes of simple or multiple vertical borehole extensometers located in the vicinity of the coordimeter bases near the foundation to obtain the vertical component of the movement of these points (so measuring the three displacement components). These ideas have already been applied in some arch dams.

Careful monitoring of the hydraulic behaviour of the foundation (Fig. 1) through seepage and uplift measurements is usually made. Detailed in the design phase drainage and piezometric curtains are sometimes completed further following the information obtained from the instruments already installed.

Joint movements are quantities generally measured by means of deformeters. These movements are measured in practically all the joints in the corresponding accessible zones (crest, when justified near the dam faces or at least in one significant zone, inspection galleries, including drainage galleries, in the wall and in the floor — accessing to the structural concrete, or in the ceiling) (Fig. 1).

In addition to surface joint movements also movements at points inside the body of the dam are measured by means of jointmeters usually installed in the medium zones of the blocks or at a distance of about 1 m to the dam faces, according to the information needed. The use of jointmeters to control the opening of joints during grouting (a kind of operation already used with success) can indicate some special positions (for instance, at 1 m from both dam faces and at medium joint zone in two or three levels, in compartments where higher grouting pressures are to be applied).

In addition to the preceding ones, other physical quantities are measured when the importance of the dam justifies the installation of the correspondent instruments.

At present rotations are scarcely measured. However, as said, there is now a trend to measure this quantity again.

Concrete temperatures are also quantities generally measured in order to know the effective thermal variations inside the body of the dam. In fact, they are very important structural actions that cannot be easily computed especially when great changes of reservoir level occur. As all the other electric resistance instruments give the values of temperature resistance thermometers are installed in a supplementary way. This installation should be made in order to obtain information about the mean temperature and the thermal gradient variations along some strategic sections (Fig. 1).

Strains and stresses are also usually measured. The instruments are placed in zones where higher stresses are anticipated, i.e., along the arch crest, along the main cantilever and near the foundation haunches (Fig. 1). Stressmeter groups are usually installed near some strainmeter groups and, as said above, in some zones, with creep cells.

3.1.2. Gravity dams

In what concerns planimetric displacements measured by triangulation, the targets are distributed over the body of the dam in order to obtain the movements of different blocks, especially the higher ones and those located at differential deformability zones. Where possible, targets are installed at each block, at least one near the crest and other near the foundation. However, depending on the dam height, one or even more intermediate marks have been also installed.

Precision traverses galleries are installed in some horizontal galleries.

Plumb-lines are installed in one or more blocks in almost all dams of this type.

Vertical displacements are usually measured by precision levelling methods at points located at the dam crest. In some cases also levelling alignments have been provided in horizontal galleries or even in the drainage galleries. In galleries near the foundation, also vertical displacements have been measured by means of rockmeters provided with an anchor at a deep point.

Joint movements are also generally measured by deformeters to monitor relative movements between adjacent blocks — openings and vertical and horizontal slidings. Usually the deformeters are installed in positions similar to those in arch dams. Also electric jointmeters are usually installed inside the joints.

As knowledge of uplift distribution under gravity dams is still more important than in the case of arch dams, special care is taken in their measurement and data analysis. In what concerns drained water special attention is paid to its turbidity, as transportation of foundation materials may deteriorate the foundation strength.

Measurements of rotations by clinometers have been made. However, for the same reasons presented for arch dams, they were abandoned for a long period and begin now to be measured again.

As temperature is an important action, internal temperature measurements are usually made in sections distributed along the height of the blocks. However, due to the great thermal inertia of the thick concrete masses only a few thermometers are sufficient to characterize the distribution of those temperatures along the sections. Usually only one or a small number of blocks are thermically instrumented.

The usually low stresses developed inside gravity dams do not justify in most cases their measurement. However, in some of the higher gravity dams plane groups, couples or individual strainmeters have been placed in the highest profiles.

3.1.3. Buttress dams

3.1.3.1. Multiple arch dams

Regarding external actions also ground motions ought to be monitored when justified. However, as mentioned, only one of these dams (Aguieira) has a permanent equipment installed.

Planimetric displacements refer to targets distributed over the body of the dam (buttresses and arches, at different levels). The geometric characteristics of these dams call usually for a special triangulation network.

Plumb-lines have been installed in order to measure displacements of points near the foundation and of points of the arches and of the buttresses. Also, the geometry of these dams calls for special installations like, for instance, plumb-lines encased in external devices.

Vertical movements are observed by precision levelling of bench marks placed at the crest of the dam and along inspection galleries and in the downstream zone.

In the two existing multiple arch dams rockmeters were not initially installed. However they were further installed at Aguieira dam to measure foundation movements in some particular zones.

Internal joint movements are measured with Carlson apparatus at half-thickness in the joints of the arches and, at several elevations, in some joints near the dam faces. Surface joint movements are measured on deformeter bases in accessible zones (crest, galleries, downstream face near the foundation zone and at several elevations where external accesses are provided).

In accordance with the foundation characteristics and with the development of watertightening and drainage works in the construction phase, piezometers and drainage curtains are installed to assess hydraulic foundation behaviour.

Due to the usual small thickness of the arches the influence of temperature variations is considerable. So, in addition to the other electric resistance instruments (jointmeters and strainmeters) also thermometers have been installed.

The assessment of the stress field is very useful to analyse the behaviour of these dams. So, groups of strainmeters, provided with a no-stressmeter in the vicinity, are installed in the most typical zones. In the two existing multiple arch dams no stressmeters has been installed. However, as mentioned, together with creep cells they would be very useful.

3.1.3.2. Solid head buttress dams

Planimetric displacements refer to targets placed over the body of the dam, namely near the crest and at one or more levels on the buttresses downstream faces.

Plumb-lines have been installed to measure displacements of some points near the crest (in fact, the geometric characteristics, in particular the usual absence of horizontal galleries in the body of the dam, prevents the measurement of displacements in other intermedial zones), or of points near the foundation. However, the use of some special arrangements (plumb-lines encased in external devices) allows the measurement of displacements of other points.

Vertical movements are observed by precision levelling of bench marks placed at the dam crest and in sometimes, on the downstream zone.

In the Portuguese dams of this type rockmeters were not considered in the corresponding initial monitoring plans but they are now being foreseen as the corresponding schemes are updated.

Internal joint movements are measured with jointmeters installed at half-thickness between the heads of the blocks.

Joint opening and sliding movements are measured at the surface on deformeter bases placed in accessible zones (crest, galleries, or downstream faces near the foundation and at several elevations where accesses are provided).

The characteristics of the hydraulic behaviour of these dams and the development of watertightening and drainage works in the construction phase and the existence or not of foundation galleries, have conditioned the seepage and uplift control.

The differences of thickness between the head and the buttress web may cause certain peculiarities in the temperature pattern inside concrete (during construction

— dissipation of the heat hydration cement, or during the operation phase — due to the small thickness of the buttresses). So, in addition to the other electric resistance instruments (jointmeters and strainmeters) also thermometers have been installed.

The knowledge of stresses in some zones of the body may be very useful for the behaviour analysis of these dams. So, groups of strainmeters, provided with a no-stressmeter in the vicinity, were installed in the most typical zones.

3.2. Fill dams

In what concerns the construction phase piezometers (in foundation and in earth zones), total pressures (in interface zones between materials of different deformabilities), deformations of the body of the dam and foundation, and phreatic levels in surrounding zones may supply very useful data regarding the safety of the dam already constructed and the further behaviour analysis. In what concerns the first filling of the reservoir, the measurements characteristic of this phase are almost the same as the measurements made in the phase of operation. These will be presented for each type of fill dams considered.

3.2.1. Homogeneous dams

Surface displacements are determined by triangulation (planimetric movements) and precision levelling (vertical movements). Survey monuments are installed on the dam along certain sections distributed in order to cover the dam surface representatively. They are usually placed at the crest and at the downstream berms (if they exist). Sometimes survey monuments are also installed on the upstream face (despite their being observed only when the reservoir level is lower than them).

The bench marks (if vertical movements are measured) are usually placed at the crest and sometimes also in the berms.

Internal displacements are measured in order to know, at some selected sections, the distribution of the horizontal and vertical displacements.

Pore pressures are usually measured in one (the highest) or more sections. In each the corresponding instruments are placed in such a way that the flow net through the section can be assessed. Further to these sections the use of instruments in other places may supply important data related to the dam safety.

As the knowledge of pore pressure value in the transition zones between the body of the dam and the abutments is of great interest for the safety control, these values are also measured in some dams.

The evolution of the amount of water seepage through the dam and its relation with the reservoir level variation and with the precipitation local values are information of great interest to the evaluation of the overall dam safety conditions. So, where drainage galleries exist or when devices collecting partially or totally that water are available, the corresponding measurement is periodically made.

3.2.2. Zoned dams

Surface and internal displacements are measured in conditions identical to the precedent ones. Moreover, some internal displacements devices are placed in transition zones between different materials (Fig. 2).

Pore pressures in the clay core are measured in one (the highest) or more sections. In each, the instruments are placed in such a way that the flow net through the clay core in the section can be assessed (Fig. 2). Further to these sections the installation of piezometers in other places supply important data related to the dam safety. As happens for the homogeneous dams and for the same reasons also pore pressures are sometimes measured in transition zones between the dam and the abutments.

Total pressures in the clay core and in the interface zones between different materials are also measured in some dams as their distribution is important in the safety evaluation concerned with hydraulic fracturing (Fig. 2).

Considerations about seepage for the homogeneous dams apply here.

3.2.3. Rockfill dams with upstream impervious face

Displacements of survey monuments and bench marks placed on the crest and on the downstream face in some sections are measured by triangulation and levelling methods.

The measurement of displacements of points of the upstream face in some sections by means of slope indicators carefully selected and the measurement of displacements along transversal and longitudinal lines are also foreseen in a dam to be constructed (Apertadura, a 50 m in height dam).

As the impermeabilization of the dam is only guaranteed at the upstream face, the knowledge of partial or total flows through the dam is very important. So, the corresponding devices have been installed and are strongly recommended for future dams.

4. FREQUENCY OF MEASUREMENTS

The acquisition of data follows immediately the installation of the devices, which for most instruments occurs during the construction phase. The frequency of measurements is related to : the corresponding phase of dam life (construction, first filling, and operation); the occurrence of exceptional events (large floods, earthquakes, rapid emptyings, etc.) or the occurrence of signals of abnormal behaviour, calling for special visual inspections and for special data acquisition programs; and the type of data acquisition, namely manual or automatic.

Portuguese experience, quite different regarding concrete or fill dams, will be reported hereinafter, in what concerns manual collection of data; the automatic collection will be dealt with in point 5.

4.1. Concrete dams

The installation of the monitoring scheme is, in general, made by a technical crew permanently present in the work. The frequency of measurements can so be established in the best possible conditions to obtain the required results. So, for instance, with electric embedded apparatus, measurements are usually made : immediately before and after the installation; each 4 hours until 12 hours after; 24 hours after; every day, at the same hour, during one week; twice a week, during one month; and, once a week in the following period.

During the first filling of the reservoir, when it takes a short period of time, it is usual to maintain a local crew which is charged, in addition to a continuous visual inspection, with the data acquisition. So, accordingly to the plan set down for this phase the frequency of measurements is as thought most convenient to achieve a rapid safety assessment specially with the reservoir level at certain elevations, in which measurements of displacements by geodetic methods are made and the analysis must reach a thorough understanding of the structural behaviour.

When the first filling runs within a relatively large period of time and the actions proceeds at a slow rate, special observations are also made similarly for some reservoir levels; in the meanwhile, however, the frequency of measurements may be lower : for instance, once a week for the physical quantities considered essential for the safety assessment, and weekly or fortnightly for the others.

After the first filling the frequency of measurements is usually : weekly for the first years (usually five), for the essential physical quantities; fortnightly for the other quantities, and annual for the displacements observed by geodetic methods. For the subsequent period of time, the frequency usually decreases. However, even then, the measurement of displacements by means of plumb-lines and by borehole extensometers and of seepage and uplifts is still done once a week.

The presence of a local crew to carry out the monitoring programme and also the so important visual inspection routines is assured in almost all the large hydroelectric schemes; however, in some other Portuguese dams, despite their relative importance, crews are not present, which leads to a drecreasing of the frequency of measurements (a situation that will be necessarily corrected by the application of the Safety Regulations).

4.2. Fill dams

The installation of the monitoring scheme during the construction phase is made by the same personnel as charged with the construction quality control. As the behaviour control during this phase is of particular importance, measurements are made after the installation as soon as the conditions allow it, and their frequencies are fixed in accordance with the construction development (as happens with pore pressure or with internal displacement measurements).

Up to now, the first filling was not followed in accordance with any specific monitoring plan, perhaps due to its usually slow rhythm. However, during that phase and, as regards the earth dams, also during the first emptying, the number of observations increased. Recently, monitoring plans for the first filling were set up. The selection of the essential physical quantities for the safety control, the frequency of measurements, reservoir levels to be maintained during a certain period, are specifications contained in those plans.

In almost all these dams there is not a local crew to assure the measurements and the visual inspection routines in the operation phase. So, their frequency is significantly lower than for the concrete dams (in normal circumstances twice a year, which has been considered sufficient having in mind the good behaviour of these dams and the expected time that deterioration phenomena should take to create serious problems). However, that frequency will possibly be revised in consequence of the application of the Dams Safety Regulations. For some fill dams also the setting up of a local crew may be decided.

5. AUTOMATION OF MONITORING SCHEMES

5.1. Concrete dams

Since a long time ago the advantages have been recognized of continuous data recording for some physical quantities (especially displacements measured by plumb-lines). Thus, a few recording instruments have been used in Portuguese dams. However, the development of electronics has allowed to devise other kinds of automation. Following the international trends in this matter a research program to study and apply the automation of monitoring activities has been set up. As the ability to fulfil rapid data processing and efficient behaviour analysis (especially having in view the immediate safety control) were considered a priority (in fact, almost all Portuguese dams are accessible all over the year, thus not demanding urgent development of automatic acquisition of data) and moreover as the necessary equipment already existed, those were the primary goals of the research program. Besides, it was necessary to guarantee the efficient processing and analysis of the data (thus considerably enlarged) that will arise from further automatic data acquisition. So, during some years a halt was put to the development of the automation of data acquisition. In 1984, during the safety control operations of an arch dam submitted to a large repair, mainly involving its foundation, a test of automation of data acquisition was made. As a consequence of the relative success of this experience a study has been developed having in view automatic data acquisition, checking operations to be developed at the dam site, transmission between this site and the processing center, and type of procedures to implement at the host computer to guarantee a certain level of automatic safety evaluation. This study includes a preliminary selection of the physical quantities to be automatically collected, thus considered essential to the dam safety control.

In what concerns automatic data acquisition some experiments are being developed connected with data transmission. Moreover, in some cases, information processed in local minicomputers was transmitted to host computers installed in processing centers.

Even for the schemes without automatic data acquisition, plans exist for the permanent installation of minicomputers at the dam sites, where the information will be preliminarily processed and checked and will after be transmitted, by " modem ", to the processing centers.

As said above, a research program has been developed to automate data processing and storage. As a consequence data processing follows a sequence such as : input of data in the computer (the record forms are set up in order to facilitate this task); validation of data (which means the detection of the major errors); calculation of the usual physical quantities from the data; validation of these quantities (by means of model analysis), and data storage. The storage is made in files, which are up-dated after each new addition, in such a way that any group can be easily extracted (grouped by type of quantities and ordered by dates or following any other criteria). The groups can be used by subroutines (e.g. for the automatic drawing of diagrams, for calculation of results of quantitative analysis, etc.), thus supplying the necessary elements for the interpretation of the dam behaviour.

5.2. Fill dams

Up to now automatic data acquisition and transmission were not considered as an immediate aim. In fact, the already mentioned absence of local crew in almost all the fill dams and the consequent low frequency of measurements rank that automation as a second class problem.

Recently, information correspondent to these dams have been also processed and stored in a way similar to that of concrete dams. Only in what concerns the check of quantities some difficulties arise due to the non-existence of quantitative analysis, up to now, in such terms as it is used in the concrete dams field. In fact, the more complex rheologic behaviour of the correspondent materials does not allow, at least for the moment, the setting up of models with the possibility of predicting physical quantity values by means of mathematical models similar to those used for concrete dams. However, in the next future, it seems possible to implement models to achieve also this goal. So, for the time being, data analysis in automatic processing is similar to that previously reported for concrete dams, except in what concerns validation of the physical quantity values.

6. ANALYSIS OF RESULTS

6.1. Concrete dams

A first stage of analysis is performed following the procedures already mentioned, by computer routines. A second stage of analysis, developed by the safety control responsibles, is based on the information obtained by the data storage management (diagrams with the evolution of results, diagrams and drawings representing particular situations — distribution of displacements, stresses, uplifts, seepage temperatures, etc.), and also on the information from the visual inspections or from existing documents reporting facts related to the dams safety.

Following the usual systematic classification, this kind of analysis of results can be made either by a qualitative or by a quantitative method. The former consists of the detection of a correlation between actions (usually due to the hydrostatic level and the temperature) and the correspondent physical quantities, on the diagrams of their evolution (so comparing identical situations, analysing trends of evolution, etc.), or comparing results from different nature but with an understable physical relationship. The latter method consists of the setting up of a quantitative model (of statistic, deterministic or hybrid type) that allows to predict the values of some physical quantities, taking into account the material properties, geometric characteristics, external connections of the body of the dam, the previous behaviour of the dam, etc., in suitable conditions, having in mind the model type. When an acceptable agreement between the predicted and the observed values is obtained, the behaviour of the dam can be considered normal, in what concerns those quantities. When this does not happen a deeper analysis becomes necessary to verify if this fact is due to the model insufficiency or inadequacy or to a real defective behaviour of the dam.

The quantitative analysis can be made only for one specific physical quantity (for instance the radial component of the displacement of one point of a dam), or for a set of quantities (whether of the same type or not). In the former case the correspondent analysis informs about the behaviour regarding this specific quantity. So, situations may occur in which a deficient behaviour will not be evident from this quantity. On the other hand, when a model can predict values of a set of quantities, considered as representative of the overall behaviour of the dam, it can be said that the dam behaves normally if one obtains a good agreement between the predicted and the observed values. However, even in this case, a situation may also occur which, for instance, only can be detected by visual inspection, due to the fact that the abnormal behaviour has not yet caused disturbances in the physical quantities analysed. Thus the analysis of the results must always be considered as a partial diagnostic, more or less enveloping (depending on the effective representativeness of the set of the physical quantities analysed).

As the analysis of the results is a continuous activity, as regards the Portuguese concrete dams, it must be based on simple procedures, frequently helped by automatic activity, as regards the Portuguese concrete dams, it must be based on simple procedures, frequently helped by automatic routines. However, a deeper analysis is periodically performed involving all the information available. The periodicity of this analysis depends on the life phase of the dam. Usually, after the first filling of the reservoir, after the first years of normal operation and further every five or, at least, ten years, a very detailed report is prepared. Besides these, annual or biennial reports that analyse the results more directly related to the dam safety, are also prepared.

As the reliability of the data is essential to correctly achieve dam safety control, local minicomputers with a certain ability to execute a preliminary verification of the dam safety based on adequate models, are being installed. Thus, even without automatic acquisition, the monitoring data may be immediately checked and rapidly corrected if any error occurs. The data transmission between the dam site and the host computer is then an easy operation only dependent on the existence of telephonic lines connecting them.

6.2. Fill dams

As mentioned, the frequency of data acquisition for fill dams is much lower (up to now) than for concrete dams. So, the analysis of the results must be done immediately after the correspondent measurement campaign. The usual analysis lies on a qualitative evaluation of the trends of the evolution of results. However, after the construction phase, the first filling of the reservoir, a rapid partial or total emptying (this, in the case of earth dams), after a certain period of normal operation, after some years passing over the last report, or after the occurrence of singular happenings like those already mentioned, especial documents are prepared with a very detailed analysis.

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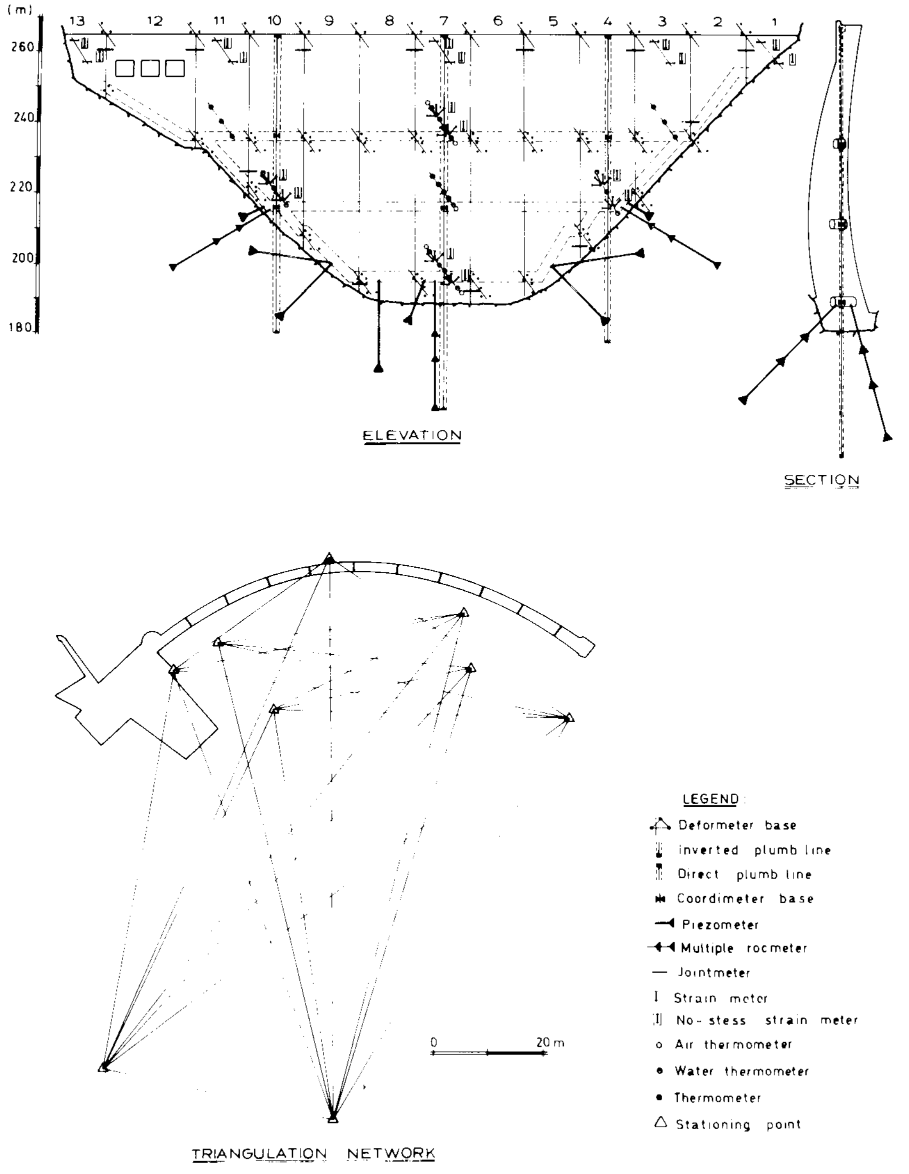

Fig. 1 – Monitoring scheme (arch dam)

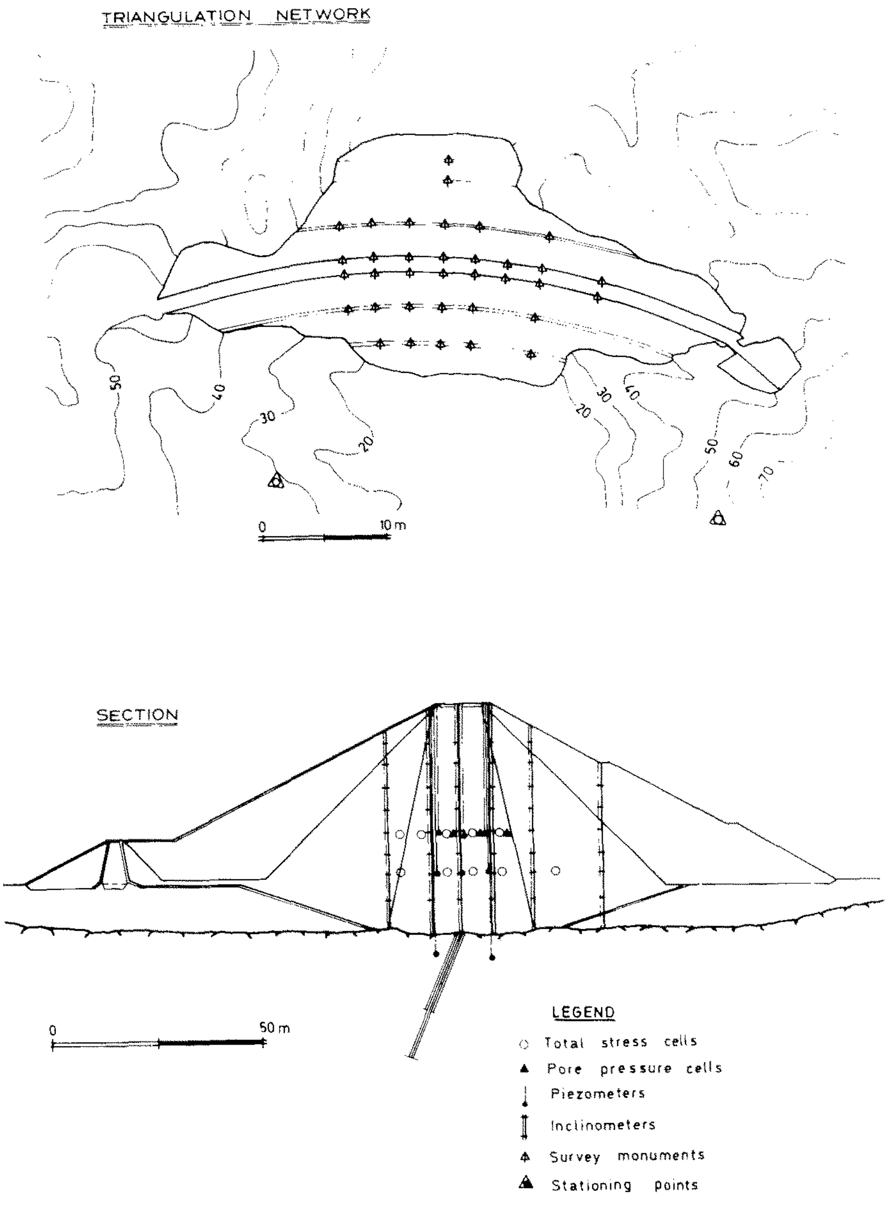

Fig. 2 – Monitoring scheme (zoned fill dam)

Appendix I
Annexe I

REPORT BY THE SOUTH AFRICAN NATIONAL COMMITTEE

In the Republic of South Africa (RSA) most of the dams higher than 40 m which were constructed during the past two decades were to some extent equipped with structural monitoring instruments. Prior to 1986 there were no legal or statutory requirements for monitoring of dams and their foundations. Dam safety legislation introduced in 1986 requires that details of monitoring systems for new dams should be submitted for approval while the adequacy of systems for existing dams should be evaluated every five years.

When the present levels of instrumentation at dams in the RSA are compared with the guidelines suggested in the ICOLD Bulletin 41, only a few dams comply. The present objective is to gradually upgrade the level of instrumentation at existing dams by taking into account the actual condition of the dam, the present level and reliability of instrumentation as well as the hazard potential associated with the project.

Attempts to write specific guidelines for use in the RSA have not been successful due to the multitude of restrictions and limitations associated with existing and new dams each requiring a monitoring system with its own peculiar character. Individuals have therefore applied their experience and judgement in the design of monitoring system for specific sites, concentrating on simplicity and reliability.

Since most large dams in the RSA are owned by and therefor engineered by or on behalf of the Department of Water Affairs (DWA) the practices and experience reported here mostly reflect those of this organization.

Through the years definite preferences emerged with respect to certain types of instruments. With the experience gained certain precautionary measures became established practice. These, as well as some thoughts on the processing and evaluation of the data, are presented. Several examples of typical monitoring applications are referred to briefly.

1. BACKGROUND

It is important to note a number of specific considerations that have had an influence on the acceptance of the practices described here.

Firstly, as a developing country only limited resources are available and hence priorities for the allocation of funds have to be assigned considering all the needs of the population. In comparison with Central Europe valleys downstream of major dams are generally not as densily populated and the hazard potential is thus relatively lower.

Secondly the climate in the RSA for all practical purposes allows accessibility to all dams throughout the year. Approximately half the country is arid or semi-arid with large annual fluctuations of rainfall.

Thirdly, the majority of dams owned and operated by DWA are staffed by at least a local operator/caretaker with some maintenance staff living on or close to site. Most sites are situated in remote areas hundreds of kilometers away from the Head Office of the organization where staff ultimately responsible for dam safety evaluation are stationed.

2. DESIGN PHILOSOPHY

Although DWA has no written policy on the instrumentation of dams a clear trend can be recognised in designs produced during the past decade. The underlying philosophy behind the design of monitoring systems requires that several aspects should be evaluated in order to design the optimum functional instrumentation lay-out for a particular site. These are, among others :

(i) the function of the instrumentation system;

(ii) the phase in the lifetime of the dam for which the system is required (e.g. pre-construction, construction, initial filling, normal operation, etc.);

(iii) the physical conditions of the dam (e.g. geology, design assumptions, hazard potential, etc.);

(iv) the particular operational conditions (e.g. the ability and attitude of the observers).

The reasons for providing a monitoring system are well known. However, in recent years new or additional instruments have been installed at existing dams in an attempt to explain unexpected behaviour or to determine the possible causes of particular distress signals or simply to provide additional dam safety monitoring. In some cases the observed behaviour was used as input for the design phase of betterments to existing dams.

The particular conditions of a given site which could affect the design of a monitoring system, are listed in Table 1. For new installations i.e. during the pre-construction and construction phases all the identified items may not be appropriate, but in all instances the proposed surveillance is influenced by the other factors. The design of the monitoring system should therefore meet the requirements determined by the remaining items on the list. It should be noted that surveillance forms part of the so-called " hygiene factors " (see Table 1) which refer to those factors that determine the environment in which the dam would be operated. When a dam is staffed with competent operators and the quality of inspections can be expected to be good, the surveillance will be enhanced by visual inspections of a better quality. When it is the other way round, additional instrumentation will have to be provided to compensate for the deficiencies in visual inspections. These factors will to a large extent determine whether automation of data collection and processing is required.

There is no formula to relate particular site conditions to numbers of instruments required or to identify the parameters that should be monitored. However, studying existing monitoring systems of similar projects or considering the suggestions in ICOLD Bulletin 41 serves a good purpose in giving a first and general indication of the parameters to be measured and the required read-out frequencies. Sound engineering judgement should however be applied to decide on the most appropriate design.

In the selection of the particular instruments and data collection system a high premium is to be placed on simplicity and reliability without sacrificing on the requirements of accuracy, data collection and processing.

The different steps to be followed during the design of a monitoring system are summarized in Figure 1.

3. PREFERENCES

Through success and failure of instruments during the past two decades certain preferences have evolved. These preferences and associated practices are briefly outlined in the following paragraphs.

3.1. Displacements

Displacement measurements are considered to be the most practical way of monitoring overall structural performance of a dam and its foundation. This is especially so with respect to concrete dams and their foundations.

a) *Concrete dams*

For the measurement of relative structural displacements mechanical type pendulums with optical reading tables are preferred. Some telemetering-type reading tables proved to be unacceptable due to drift problems. Geodetic surveying is considered the most feasible method of measuring " absolute " displacements. These methods incorporate precise levelling and triangulation. The latter can be to targets on top or on the face of the dam. For many existing dams this method is the only practical solution.

Accuracy of measurements are improved by using high precision electronic distance measuring instruments. Lay-outs for a number of major arch dams were recently upgraded by including traverses in the galleries and drainage tunnels with the following advantages above the original triangulation scheme :

- observations under all weather conditions;
- improved observation due to the increased number of stations;
- by linking the traverse with the pendulums and external triangulation network, rigid body displacements of the foundations and structural deformations of the wall can be separated;
- opportunity for selected measurements at lower cost.

When upgrading the monitoring system of existing concrete dams the installation of pendulums are frequently not possible. In such cases installation of a series of tiltmeters is a feasable solution. Tiltmeters could either operate on a electrical or optical principle. Devices of the latter type have been found to be accurate and relatively inexpensive during recent applications.

A simple but very reliable instrument for measuring relative movement across cracks or joints in three dimensions, is the 3 D-displacement device. Displacements accurate to two decimals of a millimetre are obtained by using a digital micrometer.

A portable instrument to measure actual crack widths (one dimensional) is the Wexham crack width meter (expensive but accurate to 0.02 mm) or the DWA developed ID crack width meter (accurate to ± 0.1 mm). The latter was designed for use during field inspections and requires the observer to match the width of the crack with the corresponding marking on a transparent plastic strip.

b) *Embankment dams*

Internal settlement in embankment dams measured along a line in the transverse direction, i.e. along a cross section, can be monitored successfully and relatively cheaply by means of a group of hydraulic settlement cells, which are easy to manufacture.

For measuring settlement and other relative movements on the completed embankment or berms, levelling and triangulation are preferred. A problem often encountered with earth dams is the presence of unstable soil surrounding the dam making it difficult to locate stable survey pillars.

Settlement along a vertical axis is usually measured by installing magnetic rings around an inclinometer tube at fixed levels during construction. Magnetic rings are favoured to metal plates as the reed relay switches used as sensor for the read-out device requires a lot simpler and relatively foolproof circuitry, in contrast to that of the metal detector type for plates.

Inclination is used as an indirect way of measuring displacements. The moving inclinometer with a torpedo-shaped sensor containing sensitive sensors to measure inclination is widely used in fill dams. The repeatability of measurements is unfortunately poor as problems are experienced in tracking the torpedo during its travel through the casing. Older versions of the sensor (pre-1983) were also found to be negatively influenced by cross inclinations.

3.2. Pressures

Pore pressure in partially saturated soil consists of water and gas pressure and depending on the tip used on the measuring device, pore water pressure (piezometric pressures) or direct pressure (water plus gas) can be measured with the same membrane type transducers such as the pneumatic and vibrating wire type instruments. Standpipes, and twin tube hydraulic piezometers are used to measure piezometric levels. Standpipes are simple, reliable, cheap and widely used but they are unsuitable for use in materials of low permeability or where quick response is required as these instruments need relatively large amounts of water for their operation. Under such circumstances a minimal displacement type membrane or the twin tube hydraulic type instrument is considered a better choice.

Other factors influencing the choice of a transducer are : the length of tubing or cabling, design life of the installation, reliability and accuracy.

Sensors using electrical, i.e. resistance and piezo-electrical types of operating principles are recommended only for short-term measurements. The drawback experienced with these instruments is cable damage causing electrical leaks, and stray currents, which can cause false readings (which is several times worse than no reading at all). Vibrating wire type instruments on the other hand usually stop functioning in case of cable damage. These instruments can be used with relatively long cable lengths, but zero drift problems have been experienced with these.

In the Department of Water Affairs there has definitely been a trend away from using the membrane type of instruments for long-term measurements requiring tube lengths of less than 600 m. As freezing is not really a problem in the RSA, hydraulic type sensors, using de-aired water, are favoured for installations where this method can be applied. Where read-out chambers cannot be positioned so as to allow measurement of positive pressures, the pneumatic type meters have been used successfully with nitrogen instead air.

An overseas manufacturer has developed a combined hydraulic and membrane type piezometer for the Department of Water Affairs which has passed the experimental stage and is now in the production phase. The main advantages of the system lies in the in situ calibration (and recalibration) facilities and the convenience of a digital read-out for more frequent readings.

Bourdon type pressure meters (for use with the hydraulic type piezometers) were also adapted locally. The graduated scale is engraved on a transparent face in order to be able to inspect the high quality geared movements within the glycerine filled die cast bronze backing.

For the measurement of earth pressure the hydraulic type cells with a transducer using either pneumatic or hydraulic principles to record the pressure, are favoured. However the pneumatic system has been found difficult to read where long lines are needed between the transducer and the readout unit.

3.3. Strain and stress

Strain measurements in existing concrete dams and their doundations are often required to determine the cause of observed overall response or signals of distress. When access to the stressed zone is obtainable only through boreholes, there are not many options available for measuring strain. Under these circumstances the sliding micrometer developed by Prof. Kovari is preferred to any other borehole extensometer. Despite the cost of the equipment the preference is attributed to the regular calibration facility, the accuracy of better than 10^{-3} mm/m and the continuous measuring facility along the length of the borehole (in steps of one metre). Added benefits are the possibility to locate cracks and determination of overall axial displacement in the borehole. These features offer the possibility of long-term checks on the performance of post-tensioned cables as was done in the case of the Vaal Dam. This equipment has also been installed to monitor strain due to alkali-aggregate reaction in concrete and strain due to temperature variations in fresh concrete.

Another instrument which can be used to measure changes in stress in existing concrete dams is a small diameter uniaxial stress meter previously developed for measurements in rock. This instrument is pre-loaded diametrically across the sides of a 37.5 mm diameter borehole to measure stress normal to the axis of the borehole. Up to three of these instruments can be installed in one borehole if measurements in different directions are required. A smaller bi-axial version of a similar stress meter is at present being tested by DWA for a similar application.

4. DATA PROCESSING AND EVALUATION

To date the Department of Water Affairs has followed the practice of central data processing and evaluation for most of its dams. The disadvantages of this method are fully realized and steps are being taken to reduce the lapse of time between the actual reading of instruments and the evaluation thereof. As a first step to improve on this practice the local observers at two important large dams were equipped with programmable pocket calculators to compare the measured readings of a number of key instruments with values obtained from a behaviour model. This procedure now enables evaluation of readings within a matter of hours. Simultaneously a semi-automated system using a microcomputer at the dam to read and process readings and compare these with a behaviour model is being developed. One of the main objectives of these systems is to enable the local observer to make a limited interpretation of the instrument readings expeditiously and on site without having to wait for processing and evaluation at central office. Furthermore in this country of great distances it would not be desirable to have highly sophisticated equipment on site requiring specialized technicians to operate and maintain.

5. PRECAUTIONARY MEASURES

Through the years certain precautionary measures have evolved (sometimes through bitter experience). These measures can be regarded as golden rules or points to consider seriously. Some of these will now be discussed briefly.

When designing an instrumentation system it is necessary to consider the possible modes of failure or malfunctioning of the system. Having established these it is necessary to design defensively and minimize the possibility of false readings and poor performance.

It is not only good practice to use backup systems but it is also advisable to install a " new " type of instrument of unknown performance alongside a proven instrument in order to gain experience and confidence in the new instrument.

It is further good practice to study the operating principles and design of each instrument carefully. On several occasions it has proved worthwhile for the Department of Water Affairs to sacrifice one instrument of a type in order to study its features.

It is good practice to use instruments with a good performance record. It is therefore practice in the DWA to study the behaviour of certain appropriate types of instruments before installation, e.g. vibrating wire types. Readings are taken at regular intervals under controlled conditions between the dates of delivery and installation to study their behaviour.

All sensors are recalibrated and it is sometimes important to do it at the equivalent altitude and conditions as those where the instrument is going to be used. It is a good idea to do this whenever possible on site, or else a few spot checks should be done.

Lightning protection is often overlooked — it is not only a direct hit that can cause the loss of instruments, but also the stray currents caused by the high potential gradient introduced into the ground by a nearby lightning strike.

There is no scientific explanation why a neat, tidy and well finished job should have a better chance of success, but the contrary has often been observed.

Inspections by the local dam operator and his staff, apart from the other inspections, remain one of the most valuable ways of monitoring the overall behaviour and condition of a dam. The value of inspections can be confirmed by quoting many instances where structural distress was discovered at locations with no instrumentation. As conditions are, for all practical purposes, always favourable for inspections, this remains the most important means of monitoring in the RSA.

6. EXAMPLES

All monitoring systems are unique, because they are tailored to the specific requirements. The following examples which are reported on elsewhere illustrate recent practices applied in South Africa.

6.1. Elandsjagt Dam

This 75 m high earth and rockfill dam was completed in 1983. A simple inexpensive monitoring system was provided after more sophisticated equipment was ruled out because of a less favourable cost-effectiveness ratio. The system comprises two instrumented cross-sections of the embankment. Double tube hydraulic piezometers in the core and foundations measured pore pressures and both settlement and lateral deformation were measured by means of a torpedo pulled into a horizontal duct, fitted with ring magnets, which passed from the downstream face through the transition and filter zones and into the core of the embankment (see Figure 2). Settlement was also measured at various levels in the embankment by means of vertical settlement tubes fitted with ring magnets. The earth-pressure on a large concrete conduit passing through the embankment was measured by means of Glötzl type pressure cells. External measurements included determination of partial seepage flows from two drains emerging from the chimney drain within the embankment and two drains from under the side channel spillway as well as the total seepage through the embankment and foundations at a downstream weir. Horizontal movement and settlement of points on the embankment were determined by geodetic survey methods.

6.2. Pongolapoort Dam

Construction of this 89 m high arch dam in a wide valley started in 1964. Due to non-technical reasons the reservoir was operated at low levels until 1983 when it was decided to fill the dam. Re-analysis of the dam using modern techniques indicated tensile stresses in the heel zone of the dam that could result in the formation of cracking. The monitoring system (see Fig. 3) was therefore upgraded to enable the detection of the development of a crack and the associated change in the pattern of load transfer to the foundation. To achieve this multipoint extensometers were installed in the heel zone and pairs of " stressmeters " were installed in boreholes at positions close to the outer faces of the arch to detect changes in uniaxial stress measured in the direction of the first principle stress. Convergence measurements were introduced in the gallery close to the foundation. The external triangulation network was modified and traverse measurements were introduced in the galleries and drainage tunnels.

Instruments used and procedures followed are in accordance with standard practice except for the " stressmeters ".

6.3. Vaal Dam

Raising and strengthening of the Vaal Dam, by use of amongst other things post-tensioned cables, was completed in 1985. In this 63 m high gravity dam the ISM sliding micrometer is used to monitor the long-term performance of the cables.

Measurements are taken in boreholes equipped for this purpose and which are parallel to the cables. Accurate measurements allow the detection of deformations in both concrete and rock.

7. CONCLUSION

There are no clear cut solutions which can be applied to all cases. Decisions on the monitoring of dams and foundations require consideration of specific site conditions, including the potential hazard associated with the dam. It remains a challenging task to choose the parameters to be measured, the type of instruments, cabling, read-outs, etc. in order to obtain the optimum solution to suit the particular conditions. It sometimes requires innovation beyond the normal or textbook practices.

Instrumentation can only cover selected parts of the structure. Observations of a trained observer is considered indispensable in monitoring the behaviour of a dam.

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Mr. A. L. Melvill : De Wet Shand Inc.
Dr. C. Oosthuizen : Department of Water Affairs.
Mr. T. P. C. van Robbroeck : Department of Water Affairs.

DEMANDS ON THE SYSTEM

COMPRIZING

NORMAL LOADS

1. Reliability of data

   Waterlevels
   Temperature
   Pore pressure

2. Approximations in model
3. Judgement

AND

EXTREME LOADS

1. Floods
   - Reliability of data
     - Catchment
     - Flow records
     - Precipitation
   - Approximations in model
   - No flow obstructions
   - Judgement
2. Earthquake
   - Reliability of data
   - Natural seismicity
   - Induced seismicity
   - Landslide potential
   - Judgement
3. Dam break floods
   - Reliability of data
   - Approximations in model
   - Damages
   - Judgement
4. Other or unnatural causes
   - Reliability of data
   - Military action
   - Terrorism
   - Sabotage
   - Mal-operation
   - Judgement
5. Other

CAPACITY OF THE SYSTEM

COMPRIZING

SITE CONDITION

1. Foundation
   - Reliability of data
   - Approximations in model
   - Material properties
   - Geology
   - Judgement
2. Dam
   - Reliability of data
     - Materials
     - Dimensions
     - Records
   - Design
     - Philosophy
     - Calculations
     - Criteria
     - Dimensioning
     - Lay-out
   - Construction
     - Workmanship
     - Quality control
   - Behaviour
     - No sign of distress
     - Approximation of model
   - Judgement
3. Appurtenant works
   - Reliability of data
   - Design
   - Construction
   - Behaviour
   - Judgement
4. Downstream area
   - Reliability of data
   - Approximations in model
   - Judgement

RESPONSE OF THE SYSTEM

INFLUENCED BY

HYGIENE FACTORS

- Operation

  Rules
  Competence of staff
  Communication
  Warning systems
  Emergency preparedness
  Standby equipment

- Surveillance
  - Monitoring
  - Evaluation
- Maintenance
  - Inspections
  - Quality
- Human factor
  - Qualifications
  - Experience
  - Work conditions
  - Attitude

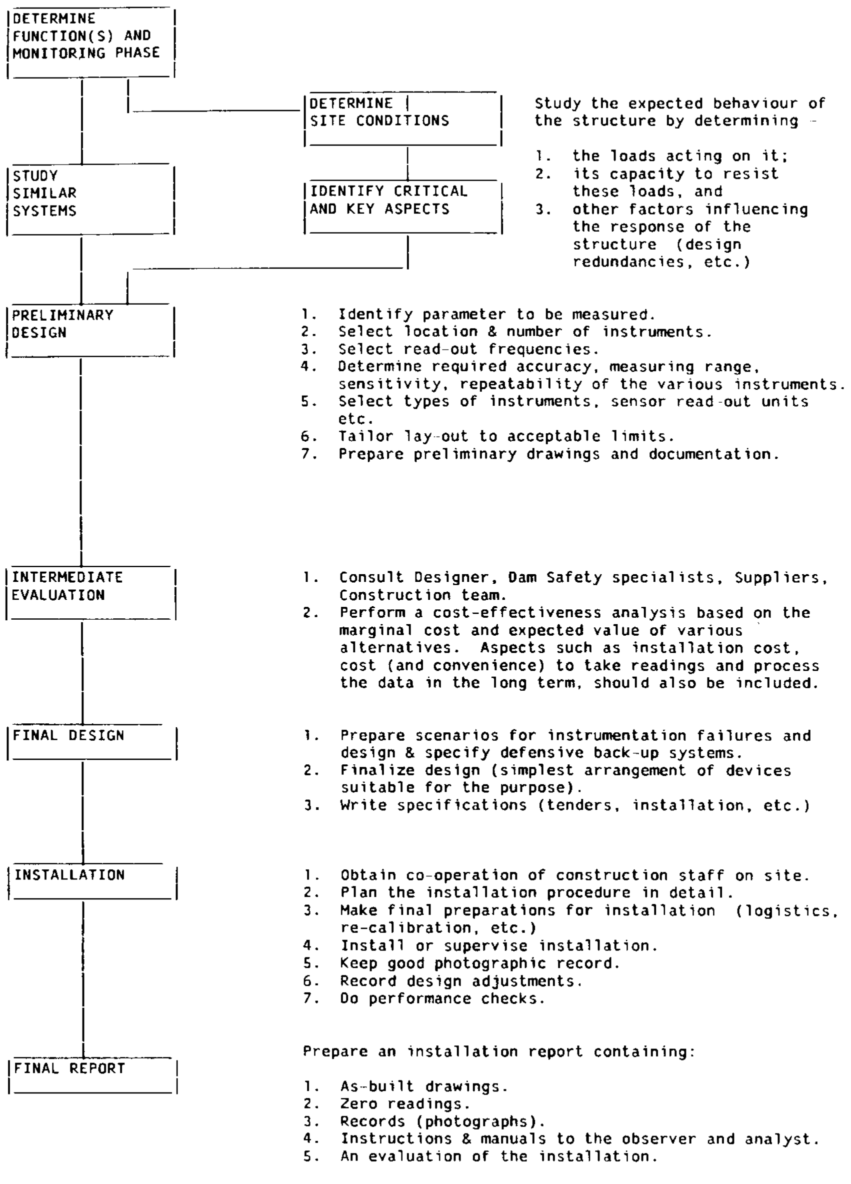
AND

DESIGN REDUNDANCIES

- Freeboard
- Overtopping resistance
- Adequate drainage
- Stability
- Special details
  e.g. Core
  Filters
- Crack resistance
- Second line defence mechanisms

OTHER SITE SPECIFIC ASPECTS

TABLE 1: LIST OF PARTICULAR CONDITIONS AT A GIVEN SITE, WHICH INFLUENCE THE DESIGN OF A MONITORING SYSTEM



Study the expected behaviour of the structure by determining -

1. the loads acting on it;
2. its capacity to resist these loads, and
3. other factors influencing the response of the structure (design redundancies, etc.)

1. Identify parameter to be measured.
2. Select location & number of instruments.
3. Select read-out frequencies.
4. Determine required accuracy, measuring range, sensitivity, repeatability of the various instruments.
5. Select types of instruments, sensor read-out units etc.
6. Tailor lay-out to acceptable limits.
7. Prepare preliminary drawings and documentation.

1. Consult Designer, Dam Safety specialists, Suppliers, Construction team.
2. Perform a cost-effectiveness analysis based on the marginal cost and expected value of various alternatives. Aspects such as installation cost, cost (and convenience) to take readings and process the data in the long term, should also be included.

1. Prepare scenarios for instrumentation failures and design & specify defensive back-up systems.
2. Finalize design (simplest arrangement of devices suitable for the purpose).
3. Write specifications (tenders, installation, etc.)

1. Obtain co-operation of construction staff on site.
2. Plan the installation procedure in detail.
3. Make final preparations for installation (logistics, re-calibration, etc.)
4. Install or supervise installation.
5. Keep good photographic record.
6. Record design adjustments.
7. Do performance checks.

Prepare an installation report containing:

1. As-built drawings.
2. Zero readings.
3. Records (photographs).
4. Instructions & manuals to the observer and analyst.
5. An evaluation of the installation.

FIGURE 1: FLOW DIAGRAM OF THE STEPS FOR THE DESIGN AND INSTALLATION OF A MONITORING SYSTEM

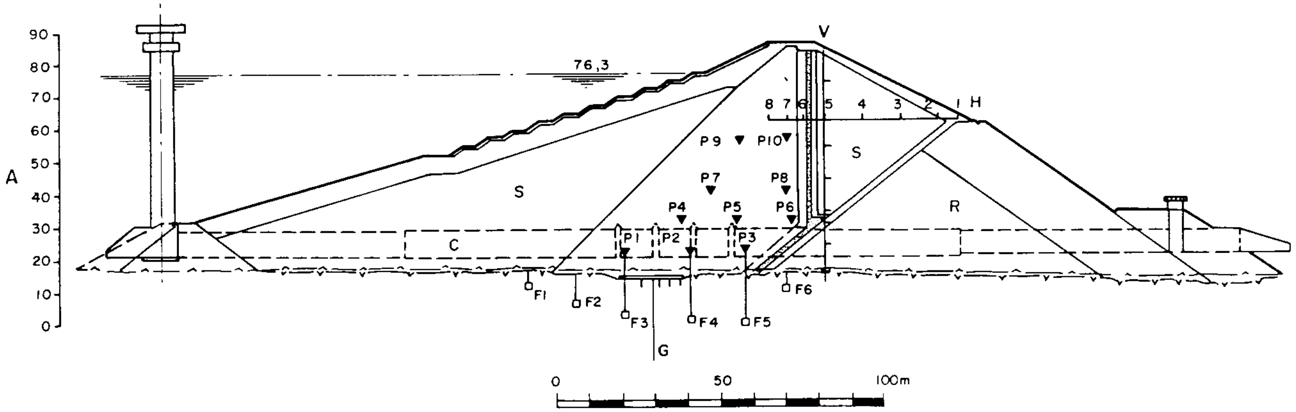


FIG.2: MAXIMUM SECTION THROUGH ELANDSJAGT EMBANKMENT

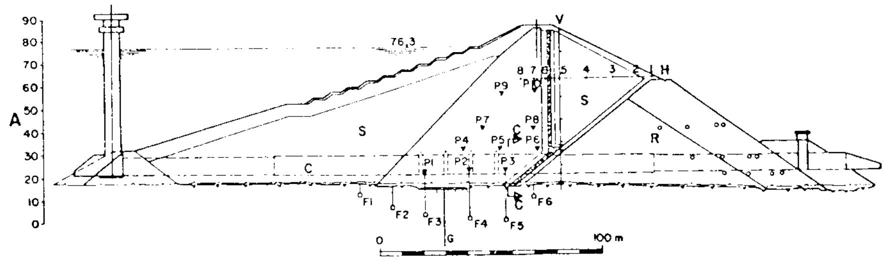


Fig. 2

Maximum section through Elandsjagt embankment

Coupe de hauteur maximale du barrage d'Elandsjagt

A. Elevation, metres above sea level	*A. Cote en mètres au-dessus du niveau de mer*
R. Rockfill zones with piezometers	*R. Enrochement avec piézomètres*
S. Shell zones	*S. Recharge*
C. Conduit founded on rock along right bank	*C. Conduit fondé au rocher, le long de la rive droite*
P. Piezometers in impervious core	*P. Piézomètres dans le noyau imperméable*
F. Piezometers in foundation	*F. Piézomètres dans la fondation*
G. Grout curtain	*G. Ecran d'injection*
H. Horizontal deformation gauge	*H. Jauge horizontale de déformation*
V. Vertical settlement gauge	*V. Jauge verticale de tassement*

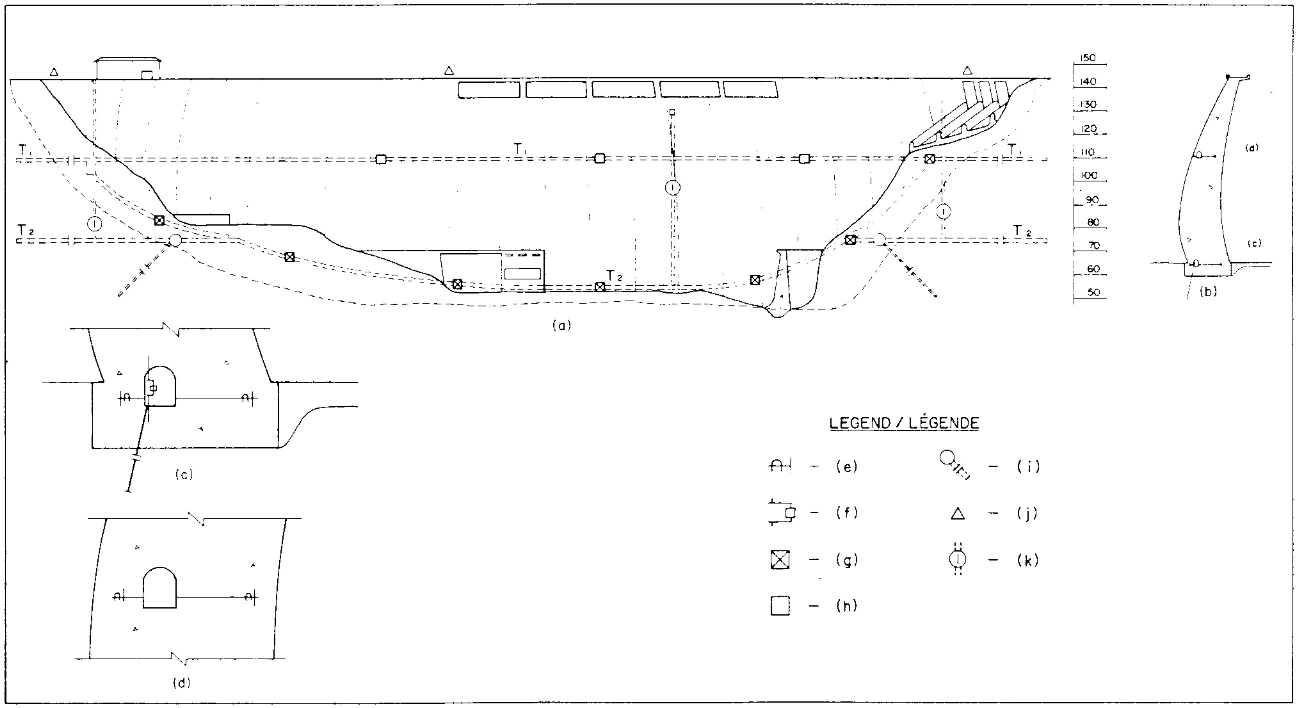


FIG.3: SOME DETAILS OF UPGRADED INSTRUMENTATION LAY-OUT FOR PONGOLAPOORT DAM

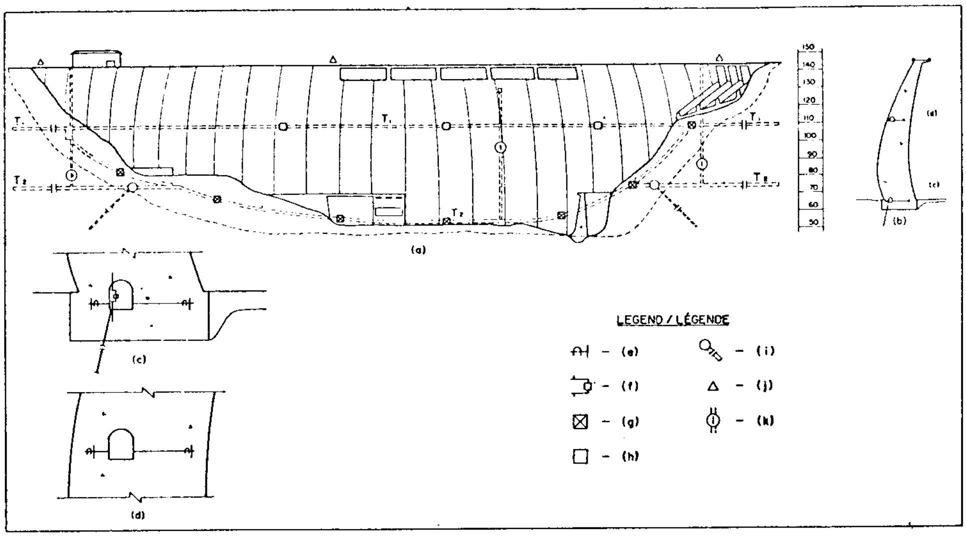


Fig. 3 Some Details of Upgraded Instrumentation Lay-out for Pongolapoort **Dam**

Quelques détails de l'amélioration de l'installation des appareils au barrage Pongolapoort

a.	Downstream elevation of Pongolapoort dam showing upgraded instrumentation lay-out	*a.*	*Élévation aval du barrage de Pongolapoort montrant l'amélioration de l'équipement en appareils*
b.	Typical cross section	*b.*	*Coupe type*
c.	Detail of « A-station »	*c.*	*Détail d'un poste « A »*
d.	Detail of « B-station »	*d.*	*Détail d'un poste « B »*
e.	Vibrating wire stressmeter	*e.*	*Jauge de pression à corde vibrante*
f.	Convergence extensometer	*f.*	*Extensomètre de convergence*
g.	A-station comprising 1 multipoint extensometer 1 convergence extensometer 2 uniaxial stressmeter	*g.*	*Poste A comprenant* *1 extensomètre à prises multiples* *1 extensomètre de convergence* *2 jauges de contraintes uni-axiale*
h.	B-station comprising 2 stressmeters	*h.*	*Poste B comprenant* *2 jauges de contrainte*
i.	Station comprising 1 deep multipoint extensometer	*i.*	*Poste comprenant* *1 extensomètre de profondeur à prises multiples*
Ti	Traverse and levelling route	*Ti*	*Chemin de traverse et de nivellement*
j.	Survey beacon	*j.*	*Borne topographique*
k.	Pendulum shaft	*k.*	*Puits du pendule*

RAPPORT PAR LE COMITÉ NATIONAL SUISSE

1. CONCEPTION GENERALE DE LA SECURITE

1.1 Organisation de la surveillance des barrages

En Suisse, il n'existe pas de règlement détaillé, précisant a priori les moyens d'auscultation à envisager, les types d'appareils et la fréquence des mesures. Cela tient au fait que la responsabilité de la sécurité des ouvrages incombe à leur propriétaire, qui est donc libre de choisir les méthodes de surveillance et les appareils qui lui conviennent, mais qui est cependant soumis à l'autorité de haute surveillance de la Confédération.

Il en résulte que les propriétaires de barrages exercent eux-mêmes la surveillance, ou la confient à des bureaux spécialisés. Mais ils sont tenus de renseigner l'autorité de surveillance :

- d'une manière générale sur les dispositifs d'auscultation de leurs barrages, fréquence des mesures, etc.,
- immédiatement en cas d'événement exceptionnel,
- périodiquement en cas de comportement normal, c'est-à-dire par des rapports annuels traitant de l'état du barrage et interprétant les résultats des mesures.

Ils doivent en outre :

- contrôler, en général une fois par an, l'état de marche des vannes des vidanges et des évacuateurs de crues,
- faire contrôler tous les cinq ans par des spécialistes en construction de barrages (ingénieurs et géologues) les ouvrages ainsi que les environs du bassin de retenue,
- tenir à jour un journal du barrage dans lequel sont consignés tous les événements importants.

Cette procédure offre toute latitude d'intervention et laisse à l'autorité de surveillance, qui peut demander le conseil d'experts, le soin de juger et de décider quelles sont les mesures de sécurité à prendre dans chaque cas particulier et selon les connaissances scientifiques ou les expériences les plus récentes.

C'est dans ce cadre général que le Comité National Suisse organise chaque année des journées d'études relatives à l'auscultation et au comportement des ouvrages. Les sujets traités sont ensuite publiés dans les revues techniques suisses. C'est donc sous cette forme que sont présentées périodiquement et discutées les expériences les plus récentes acquises par les propriétaires de barrages, les bureaux d'études ou les entreprises spécialisées dans la fabrication et le montage des appareils d'auscultation, avec le concours de l'autorité de surveillance.

Appendix J
Annexe J

REPORT BY THE SWISS NATIONAL COMMITTEE

1. GENERAL SAFETY CONCEPT

1.1 Organization of dam monitoring

In Switzerland there are no detailed regulations defining a priori the means to be employed for monitoring dams, the type of apparatus and frequency of measurements. In fact it is considered that the safety of dams is the responsibility of their owners, who are free to select the most suitable and convenient monitoring methods and equipment, subject to approval by the Swiss Federal surveillance authorities.

As a result of this policy the owners of dams either carry out their own monitoring or entrust this task to specialists: However they are bound to inform the surveillance authorities on the following :

- in general regarding monitoring arrangements on their dams, frequency of measurements, etc.,
- immediately in case of unusual events,
- periodically in case of normal behaviour, by submitting annual reports on the state of the dam with analysis of measurements.

The duties of dam owners include :

- carrying out inspection about once per year on the operational condition of bottom outlet gates and spillway gates,
- having the dam structure and reservoir embankments checked every five years by dam construction specialists (engineers and geologists),
- keeping an up-to-date log in which all important events concerning the dam are recorded.

This procedure offers considerable latitude of intervention and allows the surveillance authorities (who are free to consult experts) to take the final decision on safety measures to be taken in each particular case, in accordance with the latest state of scientific knowledge and the most recent experience.

The Swiss National Committee organizes a seminar each year on the monitoring and behaviour of dams. The subjects treated are subsequently published in Swiss technical reviews, and it is in this form that the latest experience acquired by dam owners, consulting engineers and specialist firms in the manufacture and installation of monitoring equipment is periodically presented and discussed, in collaboration with the surveillance authorities.

1.2 Concept de la sécurité

En résumé, le concept de la sécurité repose sur :

- le contrôle, et au besoin l'amélioration, des dispositions constructives et de l'état du barrage,
- les inspections visuelles,
- le contrôle du comportement des ouvrages au moyen d'appareils appropriés dont les mesures doivent être interprétées immédiatement.

En effet, il faut qu'un événement extraordinaire puisse être identifié assez tôt pour que les mesures préventives puissent être prises à temps. Si, lors de l'analyse continue de la situation, on devait s'apercevoir qu'il n'est plus possible de maîtriser l'événement, il resterait la possibilité :

- de limiter ou d'abaisser le niveau de la retenue,
- et en dernier ressort de déclencher l'alarme-eau (qui n'est pas traitée dans le présent bulletin).

1.3 Responsabilités et pouvoirs de décision

Pour éviter toute perte de temps en cas d'événement extraordinaire, il est indispensable de fixer pour chaque barrage, sous forme d'un règlement de surveillance :

- quels sont les organismes responsables de la sécurité, par exemple :
  - . gardien du barrage,
  - . service d'études du propriétaire,
  - . service d'exploitation du propriétaire,
  - . bureau indépendant, spécialement mandaté,
  - . experts;
- quelles sont les tâches et les pouvoirs de décision à chaque échelon, pour :
  - . visite des ouvrages (annuelles, mensuelles, hebdomadaires),
  - . lecture des appareils,
  - . interprétation des résultats,
  - . mesures à prendre en cas d'événement extraordinaire;
- quelles sont les autorités à informer :
  - . périodiquement sur le comportement des ouvrages,
  - . immédiatement en cas d'événement extraordinaire.
- Le rôle du gardien de barrage. Dans le schéma d'organisation de la surveillance, les gardiens de barrage jouent un rôle essentiel; l'expérience a montré que ce sont eux qui, les premiers, ont détecté et annoncé un événement inhabituel.

1.2 Safety concept

In summary, the safety concept is based on the following :

- the checking and if necessary the improvement of structural design and dam condition,
- visual inspection,
- monitoring of dam behaviour by means of suitable measuring equipment providing results which can be immediately interpreted.

In actual fact it is essential for any unusual event to be identified soon enough to allow preventive measures to be taken in good time. If, during the course of continuous analysis of the situation, it is no longer found possible to master such events, the following possibilities remain :

- limit or reduce the reservoir retention level,
- as a last resort release the public warning system (floodwater alarm), not treated in the present report.

1.3 Responsibilities and authority

In order to avoid any loss of time in case of unusual events, it is indispensible to establish surveillance regulations for each dam dealing with :

- Responsibility for dam safety, for example :
  - . the dam keeper
  - . the dam owner's consulting staff
  - . the dam owner's operating staff
  - . independant consultants under special assignment, or
  - . dam experts;
- Tasks and powers of decision at each level, with regard to :
  - . dam inspection visits (annual, monthly, weekly)
  - . taking readings
  - . interpretation of results
  - . measures to be taken in case of unusual events;
- Authorities to be informed
  - . periodically regarding dam behaviour
  - . immediately in case of unusual events.
- Role of the dam keeper

  The dam keeper plays an essential role within the monitoring organization. Experience has shown that it is he who is the first to detect and report any unusual events.

2. VARIABLES PHYSIQUES A CONTROLER

Il y a lieu de distinguer entre :

- les mesures destinées à une analyse détaillée et complète du comportement du barrage (ou d'une masse susceptible d'un mouvement) permettant de déceler assez tôt un danger, et
- les mesures destinées à compléter ou améliorer les connaissances de l'ingénieur en vue de projets futurs.

Nous ne traiterons ici que des premières qui sont essentiellement :

Pour les barrages en béton :

- le niveau de la retenue,
- les déformations du barrage et du sous-sol (par pendules, mesures géodésiques, nivellements, rocmètres, extensomètres),
- la température du béton (nécessaire si l'on veut étudier le comportement du barrage à long terme, notamment son fluage, par la méthode des déplacements compensés - voir paragraphe 6.3),
- les sous-pressions (au contact béton-rocher, et à l'intérieur de la fondation rocheuse),
- le débit des drains et des infiltrations,
- cas échéant, le débit des sources à l'aval.

Pour les digues :

- le niveau de la retenue,
- les déformations (notamment le tassement) du couronnement, des parements, d'un certain nombre de points à l'intérieur,
- les pressions interstitielles en des points choisis de façon à obtenir des profils d'écoulement,
- le débit et la turbidité des infiltrations,
- cas échéant, le débit des sources à l'aval.

3. SYSTEMES DE MESURE

Préambule

Nous donnons ci-après un certain nombre d'exemples caractéristiques de la disposition d'appareils destinés à mesurer les paramètres les plus importants.

2. PHYSICAL VARIABLES TO BE MONITORED

It is necessary to distinguish between :

- measures intended for detailed and comprehensive analysis of dam behaviour (or of masses susceptible to movement), permitting early recognition of dangerous situations, and
- measures intended to complement or improve engineering knowledge with a view to future projects.

In the present report only the first measures mentioned will be treated :

For concrete dams

- reservoir water level
- deformations of the dam and foundations (measured by plumblines, geodetical surveys, levelling, rockmeters, extensometers)
- concrete temperature (required for studying long-term dam behaviour and movements by the compensated displacement method, see paragraph 6.3)
- uplift pressures (at the interface between concrete and bedrock and within the rock foundations)
- drain and seepage flows
- the discharge of any springs downstream of the structure.

For embankment dams

- reservoir water level
- deformations (especially settling) of the dam crest, dam faces and a number of points inside the embankment
- pore pressures taken at selected points in order to establish the seepage line
- seepage flow and turbidity
- the discharge of any springs downstream of the structure.

3. MEASURING SYSTEMS

Preamble

In the following a number of typical instrumentation arrangements for measuring the main parameters are described.

3.1 Pendules Fig. 1 (Barrage de Sta Maria)

Si la forme de la section verticale (parce qu'elle est trop mince ou trop courbée) ne permet pas l'installation d'un seul fil, on pourra prévoir 2 ou davantage de fils, décalés d'amont en aval. Le pendule inverse (maintenu vertical par un flotteur) permet de rattacher aisément les déformations du barrage à un point de la fondation assez profond pour que son déplacement puisse en général être considéré comme négligeable (mais ce n'est pas toujours le cas). Dans le sens transversal à la vallée, on disposera si possible les pendules de façon symétrique par rapport au talweg.

3.2 Visées verticales Fig. 2 (Barrage de l'Hongrin)

La minceur et la courbure de la section verticale d'un barrage-voûte ne permettent pas toujours l'installation de pendules sur toute la hauteur. Une solution de rechange consiste à viser un certain nombre de cibles sur le parement aval, à partir d'une station située au pied de la section verticale, elle-même reliée à la fondation par un pendule inverse. La mesure d'angles verticaux est toutefois plus délicate qu'une mesure aux pendules.

3.3 Réseau de mesures géodésiques Fig. 3

Les mesures géodésiques ont été les premières utilisées pour suivre le comportement d'un barrage. Elles consistaient à viser des repères scellés dans le parement aval de l'ouvrage, à partir de points supposés fixes en aval de celui-ci. On obtenait ainsi, après une interprétation laborieuse, ce que livrent aujourd'hui les pendules.

En Suisse, les réseaux géodésiques n'ont toutefois pas été abandonnés. Ils servent aujourd'hui de dispositif complémentaire pour contrôle périodique des pendules (par exemple, tous les 5 ans) ou en cas d'événement extraordinaire.

La tendance actuelle est de mettre sur pied un dispositif spatial :

- se composant d'un réseau de mesure intérieur (stations de mesure des pendules, rocmètres et de polygonales situées dans des galeries horizontales),
- relié à un réseau extérieur calé environ au niveau de la retenue mais se prolongeant au-delà de sa zone d'influence (en aval) et éventuellement en amont du barrage.

3.1 Plumb-line equipment Fig. 1 (Sta Maria dam)

If the shape of the vertical section is too slender or too curved to permit installation of only one wire, it is possible to use 2 or more wires staggered from upstream to downstream. The inverted plumb-line (maintained in the vertical position by a float) allows deformations of the dam to be referred to a point deep enough in the foundations to be regarded as almost deformation-free (although this is not always the case). In the transverse direction to the valley the plumb-lines are arranged as far as possible symmetrically about the talweg (valley axis).

3.2 Vertical sighting Fig. 2 (Hongrin dam)

The slenderness and curvature of the vertical section of an arch dam does not always allow plumb-lines to be installed over its entire height. An alternative solution is to sight on a certain number of targets fixed to the downstream face, from a station situated at the foot of the vertical section which is referred to the foundations by means of an inverted plumb-line. Measurement of the vertical angle is nevertheless a more delicate procedure than taking plumb-line measurements.

3.3 Geodetical measurement network Fig. 3

Geodetical measurements were the first method used for determining dam behaviour. The method comprises taking sightings on targets set on the downstream face of the dam from supposedly fixed reference points further downstream. In this way the same results were obtained by laborious calculations as those now supplied by plumb-line measurements.

In Switzerland the geodetical measurement method has still not been entirely abandoned. It serves today as a complementary method for periodically checking plumb-line measurements (for example every 5 years) or in case of unusual events.

The present trend is to establish a spatial monitoring system as follows :

- an internal measurement system (plumb-line measurement stations, rockmeters and traverses situated in the horizontal galleries)
- this is referred to an external network located approximately at normal storage water level but extending beyond the zone of influence ot the reservoir (downstream) and even upstream of the dam.

La liaison entre les deux réseaux se fait soit par le couronnement (si les points de suspension des pendules en sont très proches, ou cas échéant par un plombage optique), soit en rattachant les polygonales et les pendules au réseau extérieur par des fenêtres pratiquées dans le parement aval du barrage.

3.4 Mesures d'allongement ou de raccourcissement par tiges métalliques (Rocmètres, extensomètres, fils invar)

Fig. 1 (Barrage de Santa Maria)

De tels appareils sont utilisés couramment pour étudier des cas particuliers, par exemple le mouvement d'une fissure, le soulèvement d'un massif de béton au-dessus de sa fondation. Une tige métallique, ou un fil tendu, coulissant à travers un forage gainé, est scellé à l'une de ses extrémités (qui est en général inaccessible); la mesure de l'allongement (ou du raccourcissement) se fait à l'autre extrémité (qui doit donc être accessible) au moyen d'un extensomètre. Depuis quelques années on installe aussi de telles tiges entre la galerie de pied du barrage et un point d'ancrage situé loin en amont (jusqu'à 50 ou 100 mètres) dans le rocher, lorsque le barrage ne comporte pas de pendule inverse et que l'installation d'un tel pendule serait difficile ou onéreuse.

Signalons en passant le micromètre coulissant, qui permet de suivre, mètre par mètre, le mouvement des parois d'un forage traversant un massif de béton ou de rocher très fissuré.

3.5 Sous-pression Fig. 4 (Barrage de Zervreila)

La mesure des sous-pressions s'effectue le plus souvent au moyen de forages traversant la surface de contact béton-rocher, tubés à leur extrémité supérieure et munis d'un manomètre. Comme la montée en pression peut nécessiter plusieurs heures, ou même des jours, on laisse actuellement le dispositif en permanence sous pression. Un barrage comporte en général plusieurs sections de mesure (voir Fig. 1) munies chacune de 3 à 5 prises de pression réparties d'amont en aval.

L'expérience a montré qu'à l'intérieur du massif rocheux la pression peut être égale (et parfois supérieure) à celle du contact béton-rocher. Un dispositif développé récemment consiste à placer plusieurs cellules (pneumatiques ou électriques) le long d'un même forage.

The connection between the two networks is effected at the dam crest (if the suspension points of the plumb-lines are very near, or in some cases by means of optical plumb-lines), or by connecting the traverses and plumb-lines to the external geodetical network through openings in the downstream face of the dam.

3.4 Measurements of elongation or shortening using metal rods (rockmeters, extensometers, invar wires)

Fig. 1 (Sta Maria dam)

This kind of equipment is commonly used for investigating special cases, for example crack propagation movements or lifting of concrete masses from their foundations. A metal rod or taut wire sliding through a lined boring is fixed at one end (which is generally inaccessible). Measurement of elongation or shortening is taken at the other end (which naturally has to be accessible) by means of an extensometer. For some years it has also been common practice to install these rods between the gallery at the foot of the dam and a bedrock anchorage point situated far upstream of the dam (up to 50 or 100 m) in cases where the dam will not accomodate inverted plumb-lines or their installation would be extremely difficult or too expensive.

An important feature of this equipment is the sliding micrometer, which follows metre by metre the movements of the faces of a borehole through a concrete mass or fissured bedrock.

3.5 Uplift pressure Fig. 4 (Zervreila dam)

Measurement of uplift pressure is usually carried out using boreholes through the concrete-bedrock interface. These boreholes are lined with pipes at their upper ends and fitted with manometers. Since it can take several hours, or even days for the pressure to rise to its maximum value, the whole arrangement is kept permanently under pressure. A dam generally comprises several measuring sections (see Fig. 1), each of which comprising 3 to 5 upstream-downstream pressure measuring boreholes.

Experience has shown that the pressure inside the bedrock can be equal to (and sometimes greater than) that at the concrete-bedrock interface. An arrangement developed recently consists in positioning several pneumatic or electric piezometer cells along a same borehole.

3.6 Pressions interstitielles

La mesure des pressions interstitielles dans les digues pose un problème particulier en raison de la défaillance des cellules due au vieillissement. Dans la digue de Göscheneralp on a exécuté, à titre d'essai, un tube vertical de 100 mètres de longueur et 130 mm de diamètre à travers le noyau argileux. Deux cellules de types différents (l'une pneumatique, l'autre électrique) ont été posées en 1983 à 5 nvieaux différents le long du tube. Les premiers résultats obtenus semblent concluants.

3.7 Infiltrations

La mesure des infiltrations à travers un barrage ou une digue n'est possible que si l'on dispose d'une galerie de pied (telle, par exemple, que celle représentée à la Fig. 1). La mesure des fuites très localisées est en général volumétrique. Mais il est indispensable de faire aussi des mesures globales, par exemple à l'aide d'un déversoir de jaugeage, au moins au pied de chaque rive (parfois aussi à mi-hauteur dans les grands ouvrages, ou à l'exutoire des galeries de drainage).

4. FREQUENCE DES MESURES ET DES CONTROLES

En Suisse, on ne fixe pas a priori la fréquence des mesures dans le cas de la première mise en eau ni en cas de comportement anormal du barrage. Cela est du ressort du propriétaire en accord avec l'autorité de surveillance.

Dans les cas normaux, les fréquences les plus utilisées sont :

- hebdomadaires ou bimensuelles pour les contrôles visuels :
  - . toutefois des dérogations sont admises dans les cas d'accès difficile, par exemple en hiver, ou lorsque le lac n'est pas plein;
- mensuelles pour les mesures importantes (parfois bimensuelles lorsque le lac est voisin de son niveau maximum) :
  - . pendules,
  - . température du béton (lorsqu'on l'utilise pour le calcul des déplacements compensés),
  - . tassement des digues,
  - . rocmètres (extensomètres, fils invar),
  - . sous-pression, pression interstitielle,
  - . débits (infiltrations, drains, sources),
  - . mouvement de certaines fissures;

3.6 Pore pressure

The measurement of pore pressures in embankment dams poses a special problem because of the failure of piezometers due to ageing. At Göscheneralp dam a vertical test borehole 100 metres long and 130 mm in diameter was made through the clay core. In 1983 two different types of piezometer cells, one of them pneumatic and one electric, were placed at 5 different levels along the borehole, and the first results obtained seem conclusive.

3.7 Seepage

Measurement of seepage through a concrete or embankment dam is only possible when there is a base gallery (such as shown in Fig. 1, for example). Leakage which is extremely localized is usually measured volumetrically, but it is indispensable to carry out seepage measurements on a global basis as well, for example with the aid of at least one gauging weir at the foot of the dam on each bank (sometimes also halfway up the dam in the case of large structures, or at the drainage gallery outlet).

4. FREQUENCY OF MEASUREMENT AND INSPECTION

In Switzerland the frequency of dam measurements is not defined a priori either for initial impounding or for the case of abnormal dam behaviour. This is a matter for the dam owner by agreement with the surveillance authorities.

In the normal case it is usual to carry out measurements at the following intervals :

- visual inspection weekly or every two weeks :
  - exceptions to this rule are admissible in cases where access is difficult, for example in winter, or when the reservoir is not full;
- important measurements monthly (sometimes twice monthly when the reservoir is near its maximum level) :
  - plumb-lines measurements
  - concrete temperature (when needed for computing compensated displacements)
  - settlement of embankment dams
  - rockmeter measurements (extensometers, invar wires)
  - uplift pressure, pore pressure
  - flow measurements (seepage, drains, springs)
  - movement of certain cracks

- deux fois par an (à condition égales de niveau du lac et de saison) :
  - . écartement des joints; clinomètre;
- annuelles :
  - . visite détaillée d'un ingénieur civil (si possible toujours le même),
  - . manoeuvre des vannes de vidange à lac plein (légère ouverture avec débit d'eau; ouverture totale sans débit),
  - . manoeuvre des vannes des évacuateurs de crues (si elles n'ont pas fonctionné durant l'année);
- tous les 5 ans :
  - . mesures géodésiques (mais avec possibilité d'en faire en tout temps sans délai en cas d'événement extraordinaire),
  - . expertise quinquennale par un spécialiste indépendant reconnu en construction de barrages : contrôle l'état et le comportement du barrage, de ses fondations et de la retenue; analyse le comportement des ouvrages à long terme; se prononce sur le système d'auscultation et de surveillance; en cas de besoin, contrôle la sécurité du barrage par de nouveaux calculs, ou contrôle la sécurité d'évacuation des crues.

5. AUTOMATISATION DES MESURES

Plusieurs barrages suisses sont équipés, ou en voie de l'être, d'appareils de télétransmission, souvent avec interprétation immédiate des résultats. Mais :

- ces équipements ne concernent qu'une faible partie du dispositif d'auscultation : 1 ou quelques postes de lecture de pendules, éventuellement de rocmètres, débits d'infiltration totaux;
- il est surtout admis que l'automatisation des mesures ne peut que compléter les mesures classiques, et ne doit en aucun cas les remplacer;
- il est souligné que les inspections visuelles fréquentes sont le meilleur moyen de détection d'une anomalie.

- twice yearly (under the same seasonal conditions and at the same reservoir levels) :
  - joint opening; clinometer measurements
- annually :
  - detailed inspection by a civil engineering expert (if possible always the same one)
  - trial operation of bottom outlet gates with the reservoir full (small opening with water flow, full opening without flow)
  - trial operation of spillway gates (if they have not been operated during the past year)
- every 5 years :
  - geodetical measurements (but with the possibility of carrying out these measurements without delay in case of unusual events)
  - five yearly evaluation report by an independent and recognized dam construction specialist : inspection of condition and behaviour of the dam, its foundations and surroundings; analysis of long-term structural behaviour; inspection of monitoring and surveillance system; if necessary a check on dam safety by new computations, or a check on new flood criteria.

5. AUTOMATION OF MEASUREMENTS

Several dams have been or are being fitted with remote monitoring equipment, in many cases with instantaneous processing of readings. However :

- this type of equipment only covers a small part of monitoring requirements, with 1 or more plumb-line reading stations and perhaps some rockmeters and seepage flow gauges;
- it is clear that automation is merely complementary to the classical monitoring methods, and must never replace them entirely;
- it is emphasized that frequent visual inspection is the best way of detecting any anomalies.

6. ANALYSE DES RESULTATS

6.1 Représentation chronologique

Le report graphique et chronologique des résultats est souvent le plus approprié lorsque les saisons (et par conséquent la température) ont une influence prépondérante, comparée à celle du niveau du lac.

6.2 Représentation en fonction du niveau du lac

Mais il est au contraire préférable de dessiner les variables (déplacements, infiltrations) en fonction du niveau du lac lorsque c'est lui qui a une influence prépondérante (voir Fig. 5).

6.3 Méthode des déplacements compensés Fig. 6

Une méthode d'analyse particulièrement intéressante est celle qui consiste à corriger les résultats bruts des mesures des effets hydrostatiques et saisonniers, et à établir des graphiques à "conditions égales" (cote de retenue et température). Cette méthode est surtout utilisée en Suisse (sous le nom de méthode des "déplacements compensés") pour les déplacements amont-aval du couronnement des barrages en béton, et parfois pour d'autres points d'un profil vertical.

L'évolution chronologique de ces valeurs corrigées (et l'écart-type annuel) permet d'apprécier le fluage (et en quelque sorte le vieillissement du barrage), mais permet aussi de détecter facilement un comportement anormal.

La Fig. 6 représente l'évolution des déplacements compensés de la section centrale de deux barrages-voûte au niveau du couronnement :

- Barrage de Luzzone, dont le fluage est pratiquement terminé (après 15 ans).

- Barrage de Valle di Lei, dont le fluage n'est pas encore terminé (après 22 ans).

L'effet de la température peut être pris en compte sur la base de mesures de thermomètres noyés dans le béton (ou de thermomètres à mercure introduits dans des forages descendants, à partir d'une galerie horizontale). Dans le cas d'un barrage-voûte, on disposera les thermomètres sur 1, éventuellement 2 niveaux relativement voisins du couronnement; dans le cas d'un barrage-poids, il sera utile de connaître la température d'un profil vertical, le long des parements.

6. ANALYSIS OF RESULTS

6.1 Chronological presentation

Graphical presentation of results on a chronological basis is often the most appropriate method, when the seasons (and consequently the temperature) have a much greater influence than reservoir water levels.

6.2 Presentation of results as a function of reservoir level

On the other hand it is preferable to present variables such as displacement and seepage as a function of reservoir water level in cases where the latter has a predominant influence (see Fig. 5).

6.3 Compensated displacement method Fig. 6

One particularly interesting analysis method consists in correcting the measured results with hydrostatic and seasonal effects, so that the final graphical presentation is based on "equal conditions" as far as reservoir water level and temperature are concerned. This method (known as the "compensated displacement" method) is employed above all for determining upstream-downstream displacements of concrete dam crests, and sometimes for other points on vertical dam profiles.

Plotting these corrected values (and their annual standard deviation) chronologically not only gives a clear picture of dam creep effects (to some extent the effects of structural ageing), but greatly facilitates the detection of any abnormal behaviour.

In Fig. 6 the compensated displacements are plotted for the central section of two arch dams at crest elevation :

- Luzzone dam, where creep effects have practically ceased after 15 years

- Valle di Lei dam, where creep effects are still taking place after 22 years.

Temperature effects can be taken into account by means of readings taken from thermometers embedded in the concrete (or alternatively mercury thermometers inserted into descending boreholes from a horizontal gallery). In arch dams theses thermometers are distributed at one or perhaps two levels relatively near the crest. In the case of gravity dams they are used for recording the temperature along a vertical profile along the dam faces.

Mais, à défaut de thermomètres, l'effet saisonnier de la température peut aussi être déterminé par méthode statistique, à partir des résultats bruts de la température de l'air (moyennes mensuelles ou hebdomadaires) obtenus pendant 2 ou 3 ans. La courbe "lissée" de ces températures moyennes a une allure quasi sinusoïdale; elle permet de déterminer l'écart entre la température régnant le jour de la mesure et la température moyenne annuelle (celle-ci étant l'un des paramètres "constants" de la compensation des déplacements) et, par conséquent, de calculer la correction thermique correspondante. Si le couronnement du barrage est relativement épais, la température à considérer est celle régnant quelques jours (voire quelques semaines) avant le jour de la mesure.

7. LE ROLE DE L'AUTORITE DE SURVEILLANCE

L'autorité de haute surveillance de la Confédération ne se contente pas uniquement de contrôler l'exécution correcte des tâches qui précèdent. Elle analyse également de manière critique les rapports qui lui sont soumis sur l'état et le comportement du barrage, et participe tous les deux ou trois ans aux visites de contrôle annuel et chaque fois à la visite effectuée dans le cadre de l'expertise quinquennale.

In the absence of thermometers, however, seasonal effects can be determined by statistical methods based on air temperature readings (mean monthly or weekly measurements) taken over a period of 2 or 3 years. From the smoothed average of these mean temperature curves, which is of the quasi-sinusoidal form, the temperature differential between daily readings and mean annual values can be established (the latter is one of the "constant" parameters used for displacement compensation). On this basis the corresponding thermal correction can be computed. If the dam crest is relatively thick, the temperature to be taken into account is that occurring several days (or several weeks) before the day on which the measurement takes place.

7. THE ROLE OF THE SURVEILLANCE AUTHORITIES

The Swiss Federal surveillance authorities do not rest at simply supervising the correct execution of the above-mentioned monitoring duties. They also carry out critical analysis of reports submitted to them on dam condition and behaviour. Moreover they participate every two or three years in annual inspection visits, and always attend the five-yearly visits undertaken by the experts.

N.B. : The above report summarizes some of the topics treated in the book "Swiss Dams - Monitoring and Maintenance" published by the Swiss National Committee on the occasion of the 15th International Congress on Large Dams held in Lausanne during 1985 (editorial committee : Dr R. Biedermann, R. Müller, N.J. Schnitter, C. Schum, Ch. Venzin, G. Weber).

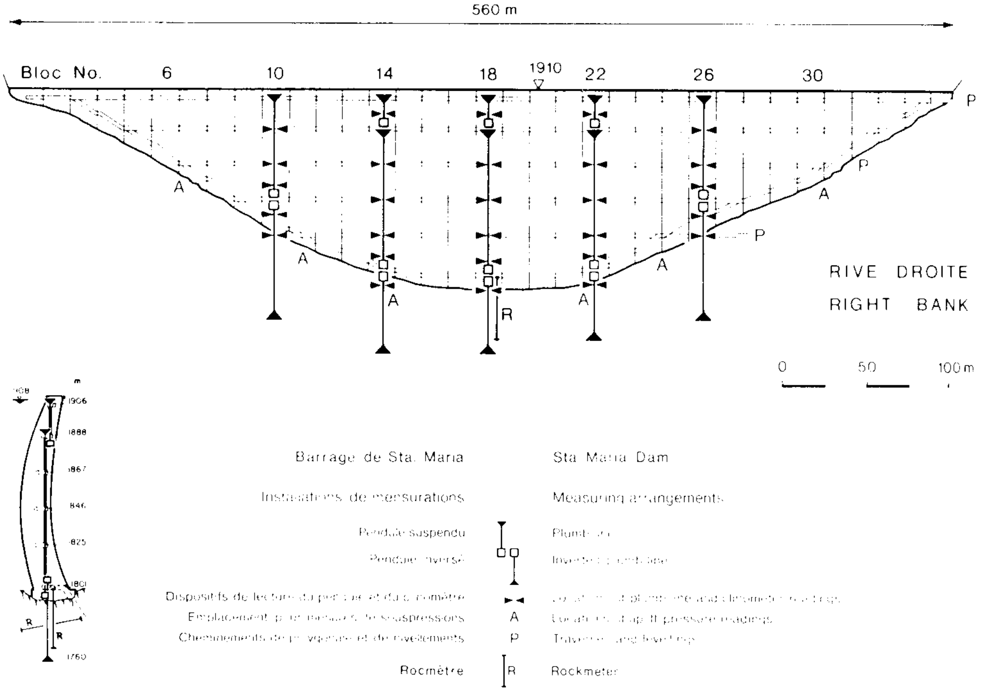


Fig. 1 Sta Maria dam. Plumb-lines, rockmeters, measurement of uplift pressures.

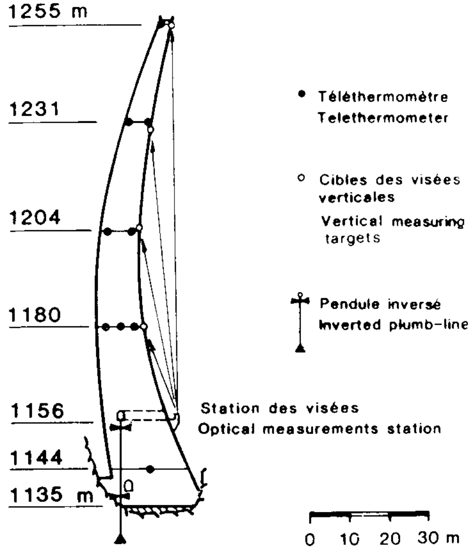
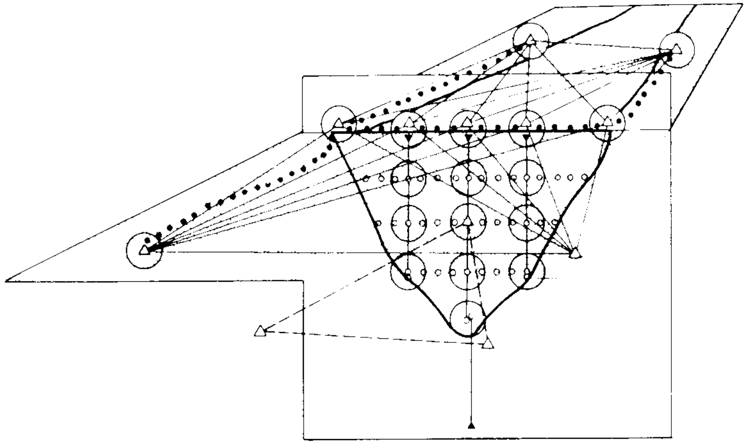


Fig. 2 Hongrin dam.

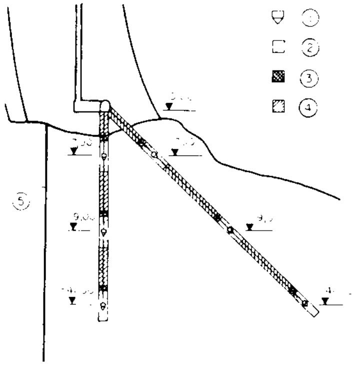
Vertical sightings.



Réseau de mesures géodésiques.
△——△ réseau de triangulation, ● ● ● ● nivellements, ○ ○ ○ ○ polygonales dans les galeries, ◯ rattachement

Geodetical measurement net
△——△ triangulation scheme, ● ● ● ● levellings, ○ ○ ○ ○ traverses, ◯ interconnections.

Fig. 3 Geodetical measurement network.



Installation de cellules de pression interstitielle à différents niveaux dans la fondation du barrage-voûte de Zervreila.
1 Cellule de pression interstitielle, 2 sable, 3 argile, 4 injections, 5 voile d'injection

Installation of piezometers at different depths in the bedrock of Zervreila arch dam.
1 Piezometer, 2 sand, 3 clay, 4 grout, 5 grout curtain.

Fig. 4 Zervreila dam.

Uplift pressure measurements in the bedrock.

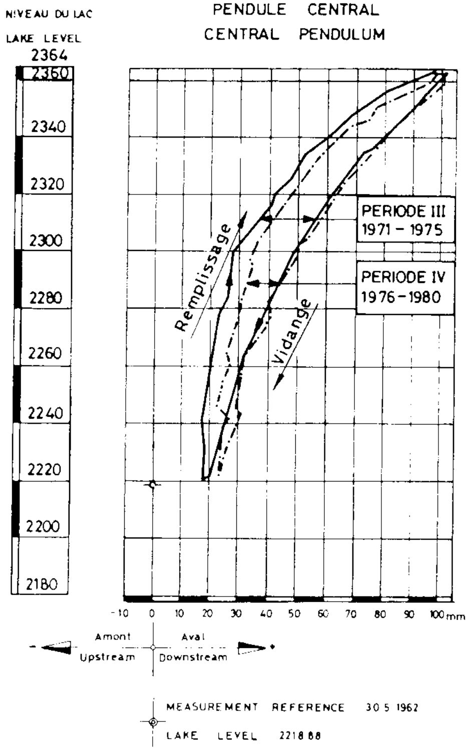


Fig. 5 Grande Dixence dam.

Crown displacements as a function of reservoir level.

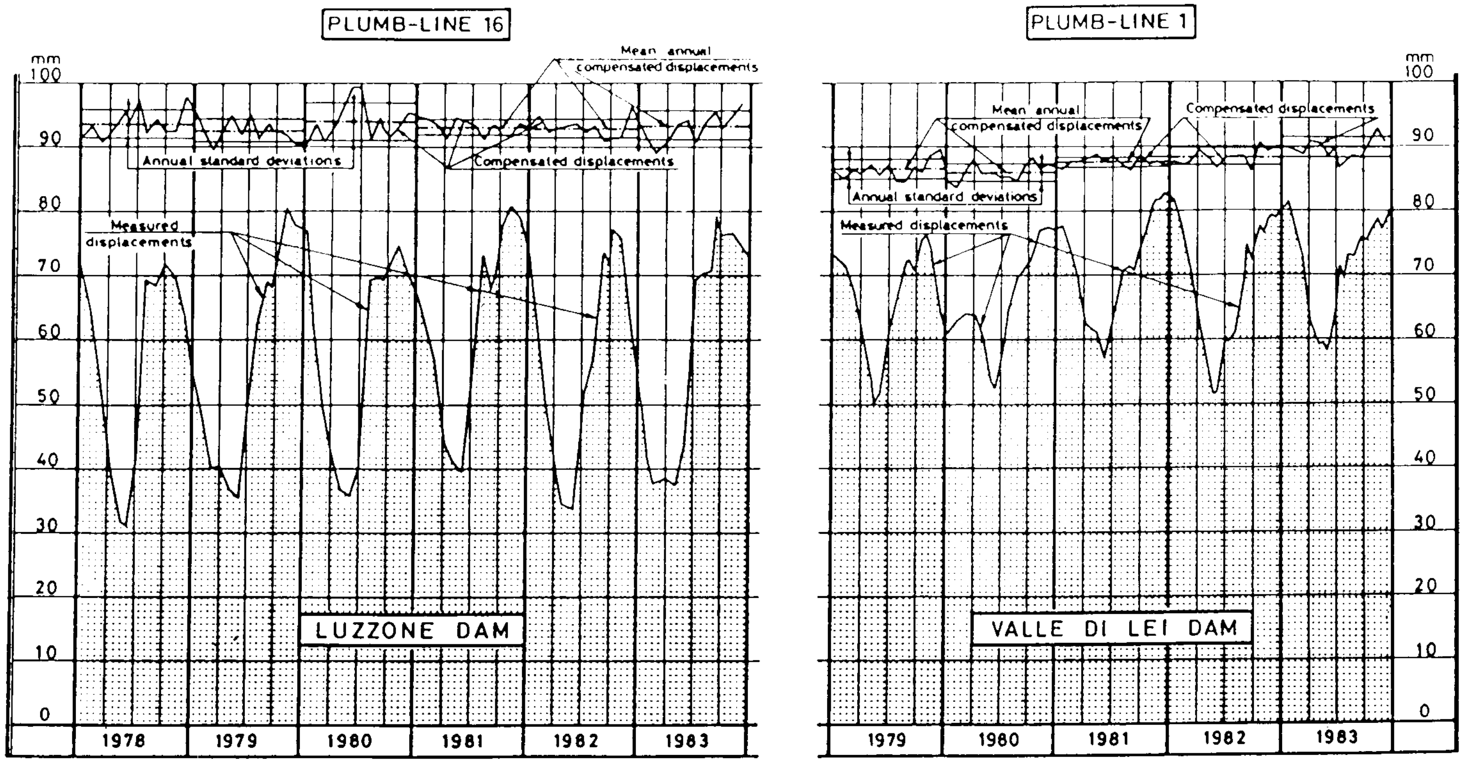


Fig. 6 Compensated upstream-downstream displacements measured on two arch dams.

Point of suspension of the central plumb-line (lowest reading station assumed fixed).

Appendix K
Annexe K

REPORT BY THE UNITED STATES NATIONAL COMMITTEE

CHAPTER I

INTRODUCTION

1.1. NEED FOR DAM SURVEILLANCE

Dams are constructed to impound large storage reservoirs and thus constitute key structures of the projects designed for development of river basin potential for irrigation, hydroelectric power generation, and other economic benefits. The water retained in a large reservoir has enormous potential energy which the dam is expected to contain throughout its operational life with complete safety.

The sudden release of impounded water in the event of failure of the dam has tremendous potential for destruction of life and property located downstream from the dam. The proper and safe functioning of these dams under all conditions is important for realization of the economic benefits and public safety and welfare. Even though dams are designed with reasonably adequate factors of safety, dam failures have occurred in the past including some recently engineered dams. Some failures happened during the first reservoir filling. For example, St. Francis Dam in California, a 62.5-m (205-ft) high concrete gravity dam failed in 1928 and Teton Dam in Idaho, a 93-m (305-ft) high earthfill dam failed in 1976. Others failed or suffered near failures after several years of satisfactory service operation, as for example due to an earthquake in 1971 the Lower San Fernando Dam, California, a 43-m (142-ft) high embankment dam. Still others experienced unacceptable deformation and distress conditions during construction. These examples show the importance of dam surveillance and need to have suitable and reliable means available in the dam for gathering information for assessing the performance and evaluating its structural safety during periods of construction, reservoir filling, and service operations.

Dam safety surveillance involves both (i) periodic visual physical inspection of the exposed areas of the dam and other structures, reservoir rim and natural slopes in the vicinity of the dam, both downstream and upstream for qualitative behavioral assessment, and (ii) monitoring dam and foundation performance by external and internal measurements by means of structural behavior measuring instrumentation for systematic evaluation of its structural safety. Detailed requirements for periodic visual inspection and monitoring performance of dams are stipulated by various federal and state regulatory agencies for dams under their jurisdiction but are not presented in this report. This report deals only with considerations applicable to monitoring performance and assessing structural safety of dams and their foundations by means of structural behavior measuring instrumentation. General considerations on reservoir instrumentation are presented in USCOLD publication entitled " General Considerations on Reservoir Instrumentation ", by the USCOLD Committee on Measurements 1979-1981.

1.2. PURPOSE OF MONITORING

The objectives of monitoring dam performance by means of structural behavior measuring instrumentation include the following :

(i) The primary and most important purpose of monitoring is to provide necessary information for assessing the performance for control and any indications of adverse conditions, and continuing evaluation of structural safety of the dam during construction, reservoir filling, and service operations.

(ii) Verification of dam design. Besides providing indications of the " health " of the structure, study of the accumulated records of monitored structural behavior assists in verification of the dam design and whether the structure is behaving as intended by comparison of the measured with the theoretically and experimentally predicted performance.

(iii) Refinements and improvements in analytical techniques. Design of dams generally entails rigorous and sometimes complex studies of forces based on rather conservative assumptions concerning material characteristics and structural behavior. These assumptions are made to provide for the " unknowns " or uncertainties in the design. Observations from the monitoring systems and assessment of the influence of various factors on structural performance of the dam help reduce these unknowns. This leads to progressive refinements and improvements in the analysis techniques, structural testing, and design parameter selection for more realistic and economic future designs.

(iv) Enhancement of our understanding of the influence of various parameters on the structural behavior of dams and development of more realistic design criteria as illustrated by the following few typical examples :

a) Influence of the columnar method of concrete dam construction on distribution of vertical stress resulting in a non-linear stress distribution. This was revealed by study of stress results of strainmeter data analysis in Shasta Dam. This factor has now been included in stress analysis procedures, taking into consideration the dam construction program.

b) Development of the present USBR uplift criterion, based on years of uplift pressure measurements at the base of concrete dams, whereby uplift head prevailing at the line of drains is assumed to be one-third of the net head. It is applicable to concrete dams with grout curtain and foundation drainage curtain downstream.

c) Identification of thermal load effects on the overall structural behavior of concrete dams as a result of the measured temperature distribution in concrete dams, particularly arch dams.

d) Enhanced understanding of the development of pore pressures in rolled earth dams and factors influencing such development based on study of monitored pore pressure data. This led to the formulation of a more rational relationship among the various parameters involved which are incorporated in present slope stability analysis procedures, for designing more dependable and safe earthen embankments.

(v) To provide early warning of any incipient or developing distress that may endanger safety of the dam, thereby ensuring timely remedial action. For example, Zeuzier Dam, a 156-m high arch structure built in 1957 in Switzerland, developed serious cracks in 1979, after more than 20 years of operation without any particular problem. Because of the sudden unanticipated development of deep cracks, reservoir was emptied. Extensive geotechnical investigations and instrumentation measurements attributed cracking to excessive and continued creeping deformation of the left abutment which was triggered by excavation of a highway tunnel 1 400 m from the dam. The dam was restored to full service following remedial treatment.

Sometimes, however, the distress may develop so rapidly that remedial action may not be possible, as was the case with Teton Dam that failed in 1976.

1.3. SYSTEMATIC APPROACH TO MONITORING PERFORMANCE

Monitoring of dam performance for structural safety evaluation is accomplished by external and internal measurements by means of structural behavior measuring instrumentation. This instrumentation comprises several different types of instruments or measuring apparatus that are embedded inside or located on the surface of the dam at various locations and periodically observed, directly or remotely, to provide information on measurements necessary for assessment of dam performance. Comprehensive, meaningful, and reliable dam performance assessment and greatest benefit for the cost of structural behavior instrumentation warrant a systematic approach to planning a monitoring program during the design stage. Application of this approach dates back to the 1930's, as outstandingly exemplified by the Hoover Dam (1936) monitoring system.

A systematic planning approach would involve defining project conditions and purpose of instrumentation, selecting types measurements, and types of instruments of required accuracy and precision for various types of measurements, and locations and orientation of instruments to provide required complete information. Decision must also be made regarding organization/personnel responsible for procurement, calibration, installation, monitoring (whether manual or automated), and maintenance of instruments; in addition, requirements for recording, processing, and analysis of monitored data, presentation and interpretation of results and evaluation of monitored performance must be decided. The objective of the systematic approach is to select a monitoring system that is not only capable of long-term accurate and reliable performance, but also economical in total cost including cost of equipment, installation, monitoring, and maintenance.

Careful attention must therefore be given to planning an instrumentation system to ensure that required information will be obtained, both during the construction period and the life of the structure. The requirements of the system and the procedures to be used for analyzing the observations should be formulated in detail and selection of the measuring devices and their location chosen to meet those requirements.

Requirements for instrumentation depend on the type of measurements desired, which depends on the site, size, type, height, and thickness of the dam, site-specific geologic and topographic conditions and need for or relative importance of the various factors for a given project. Thus, to evaluate the performance of embankments, the various types of field measurements may include : horizontal and vertical movement, stresses, pore water pressures, seepage, and earthquake effects. For a concrete dam, typical measurements include those for displacements, differential movements (deflection), internal stress, strain, rotation, deformation, joint movement, foundation seepage, uplift and leakage, and seismic vibration.

All readings must be made to the greatest precision consistent with the particular instrumentation system. The reliability of measurements depends not only on the type of instrument but also the care and skill used in making individual measurements. It is important that instruments which are performing erratically be identified early in the measurement program so that they can be repaired or replaced if such action is feasible. For measurements that are vital for control or safety of dam, at least two different types of measurement systems should be used to provide independent data to check such measurements.

The instruments selected must be capable of achieving objectives for the required period of observation. Instruments required for long-term service must be particularly rugged and capable. Procedures for installation of various instruments must be detailed during the design stage when instrument selection is made. Instruments and associated equipment should be protected from construction activities, vandalism and environmental hazards.

The personnel responsible for installation, as well as those who obtain data must be thoroughly experienced, motivated and capable personnel who must thoroughly understand the purpose and importance of the instrumentation. They should note and verify unusual instrument values and also note any unusual construction activities or other information (air temperature, reservoir level, precipitation, wind, etc.) that might affect the data. The causes of questionable data should be determined at the source to determine whether or not the data in fact reflects the true condition existing at the instrument location.

Data acquisition by automated systems precludes visual observations of extraneous field conditions that are present; therefore, the analyst who computes and evaluates instrumentation values must be very careful to note and investigate unusual trends. Programs for automated reading and data processing must incorporate safeguards to alert analysts when data exceed previously determined variation limits. All warnings must be thoroughly investigated to establish whether or not there is a trend which may indicate deteriorating conditions. If necessary, site visits should be made. Automated acquisition and data processing systems do allow the timely processing of instrumentation data. These systems also provide the opportunity to obtain data frequently in a consistent manner and to develop plots rapidly, thus enabling evaluations of integrity of dams to be made whenever needed. The automated instrumentation system performs regardless of the weather, providing data even during severe winter weather conditions that may affect ability of personnel for manual readings.

The schedule for monitoring various types of instruments should be decided, taking into consideration the anticipated rate at which various response quantities to be measured by these instruments change during construction, first reservoir filling, and service operations. More frequent readings are taken during early age and first reservoir filling to establish a database and monitor changing conditions, followed by reduced schedule for later years when the structure attains stabilized pattern of structural performance unless unusual conditions warrant more frequent schedule of observations.

This Chapter presented general introduction on performance monitoring, addressing the need for dam safety surveillance, purpose of monitoring, and need for systematic approach to monitoring performance. The following six chapters of this report present comprehensive information concerning considerations for various specific components or aspects of dam performance monitoring.

Chapter II deals with types of measurements to be made; Chapter III describes types of instruments and measurement methods; instrumentation system design is treated in Chapter IV. Chapter V deals with considerations for frequencies for monitoring different types of instruments, and Chapter VI deals with considerations for data collection, reduction and presentation of results, Chapter VII presents considerations concerning performance evaluation. The report includes an appendix : Appendix A, relating to automated data acquisition.

CHAPTER II

TYPES OF MEASUREMENTS

2.1. GENERAL

To accomplish the purpose of dam monitoring effectively, quantitative measurements relating to all operating loading, and response parameters must be made to evaluate performance. Reliable and realistic evaluation of the performance and structural integrity of the dam involves correlation of the measured response of the dam and its foundation to associated operating loads, comparison with predicted performance for comparable loading conditions, and judgment of experienced engineers. The objective of measurements is to quantify those factors that affect the integrity of dams prior to and during construction, during the first filling of the reservoir, and during service operations. This includes, where appropriate, measurements in the foundation and abutments of dams. For these reasons, it is very important that complete information be obtained regarding all the various applicable external, internal, permanent or provisional loads that affect the structural performance of the dam and its foundation. In addition, information should also be gathered concerning the environmental and ambient factors that are necessary for realistic interpretation of the results of monitored performance.

2.2. TYPES OF MEASUREMENT

Pertinent factors to be quantified are determinated by examining the basic force relationships and physical and chemical processes which are of concern in assessing dam performance and safety. This examination results in the identification and isolation of measurable parameters that can be used to assess quantitatively each factor throughout the life of the dam. All measurements must be made to the accuracy and precision to have reliability warranted by the type of measurement. The instrumentation must provide for mutually checking information to establish reliability by similar results obtained by different methods of measurement.

The types of measurements to be made depend on the type, height and thickness of dam, the site-specific geologic and topographic conditions, economic and social considerations, and the need for or relative importance of the various factors for a given project. Measurements necessary for construction control and performance monitoring of structure during filling and service operation are of the primary importance. These include dam and foundation displacement and deformation, foundation and abutment seepage, and pore pressure. Monitoring piezometric levels, ground elevations, and background seismic activity at the site prior to construction and filling a major reservoir is necessary to establish reference bases to assess the effects of water loading.

The most commonly used types of measurements are listed below followed by the type of dam to which they normally apply [Embankment (E), Concrete Gravity (CG), Roller-Compacted Concrete Gravity (RCCG), Concrete Arch (CA), Concrete Buttress (CB) or Composite Concrete/Earthfill (C/E)] :

1. Movements

Movements of dams may be grouped into three general categories, as follows :

- *Translational.* — Translational movements are movements where an entire dam or large segment of a dam moves with respect to its foundation or abutments. The movements may be either in the horizontal plane, the vertical plane, or any combination thereof.
- *Rotational.* — Rotational movements consist of movements resulting in circular or tilting motions, usually with respect to an imaginary horizontal line passing through a dam's longitudinal axis.
- *Relative.* — Relative movements commonly occur in dams wherein one or more portions of a dam move in a translational or rotational manner with respect to other portions of the dam. Such movements are especially important between a dam embankment and an appurtenant structure such as a spillway, and between individual blocks or monoliths within a concrete dam.

a) Translation	
— Horizontal and vertical	E, CG, RCCG, CA, CB
b) Rotation	E, CG, CA, CB, C/E
c) Relative	E, CG, RCCG, CA, CB, C/E
d) Strain	CG, CA, RCCG, CB
e) Differential	
— between zones	E
— at joints or at cracks in concrete	CG, RCCG, CA, CB

2. Stresses

E, CG, CA, CB, RCCG

3. Ground water and pore pressure

a) pore water pressure (neutral stress)	E
b) uplift pressure	E, CG, CA, RCCG, CB, C/E
c) groundwater elevation	E, CG, CA, RCCG, CB
d) seepage measurements	
— phreatic surface	E
— discharge amounts	E, CG, CA, RCCG, CB, C/E
— analysis of the collected seepage for - solids	E
or chemical content	E, CG, CA, RCCG

— detection of seepage paths	E, CG, CA, RCCG, CB, C/E (all types of dams)

4. Temperature

a) of water at various levels (in the reservoir and below the dam)	E, CG, RCCG, CA, CB
b) of concrete at various depths in the mass	CG, RCCG, CA, CB
c) of atmosphere	E, CG, RCCG, CA, CB
d) of soil or foundation mass	E, CG, RCCG, CA, CB

5. Seismic effects

a) accelerations	E, CG, RCCG, CA, CB, C/E
b) displacements	E, CG, RCCG, CA, CB, C/E

CHAPTER III

INSTRUMENTS AND MEASUREMENT METHODS

3.1. GENERAL

The various types of measurements generally made for assessing the performance and structural safety of the dam are described in the preceding chapter. This chapter describes the various types of instruments and monitoring devices that are generally used for such measurements, and the generalized methods and procedures for making these measurements. Also described are considerations concerning location and layout of various types of instruments and measuring devices described herein to obtain reasonably complete information for realistic and reliable evaluation of monitored dam performance. The various types of instruments provided in a major dam for gathering essential behavioral information include (i) embedded instruments for internal measurements of strains, stress, joint opening, temperature, pore pressure, and foundation deformation and (ii) those used for external measurements of structural deformation using surveying methods including plumblines, collimation and levelling measurements, and triangulation of targets on dam surface and trilateration. Needless to say, instruments of rugged construction that give reasonably accurate measurements should be preferred to overly precise, sophisticated but delicate instruments. Carlson elastic wire resistance type embedded instruments, which are dual-purpose instruments as these measure temperature also, are most commonly used in the United States for concrete dams in preference to vibrating-wire type because of proven reliability and stability for long-term measurements.

3.2. MOVEMENTS

Movements of dams may be grouped into the following three general categories : translational, rotational, and relative.

Instrument types and generalized measurement methods are discussed for each movement category in the following.

A. Translational Movements

Measurement of translational movements is normally accomplished by utilizing some form of surveying technique. All types of instruments used for the purpose of measuring translational movements of a dam have several features in common. All demand highly sensitive instruments, careful installation procedures of measuring points, and great precision while making measurements.

Measurement of horizontal translational movements commonly involves the usage of precision theodolites, EDM (electronic distance measuring) equipment, plumblines, or inclinometers. The dam is prepared for observation by the installation of permanent marker points on the dam crest and/or slopes during or immediately following dam construction. Reference monuments are also installed on the dam abutments or at locations sufficiently removed from the dam so that the reference monuments will remain unaffected by dam or reservoir induced deformations.

Movements at regular time intervals are then detected by location of a precision surveying instrument at one reference monument and sighting on another monument. Deflections to marker points on the dam may then be determined. In other cases, simple direct linear measurements are not possible and triangulation or trilateration techniques are employed. Recent developments in EDM equipment have greatly simplified those techniques while also resulting in a greater degree of accuracy in measurements. EDM equipment including their target reflectors must, of course, be properly calibrated and adjusted for atmospheric conditions of temperature and barometric pressure.

Plumblines have historically been most commonly utilized in measuring horizontal translational movements in concrete dams. Such movements result from application of reservoir pressures, cyclic and permanent temperature changes in the concrete, deformation of the foundation, or of the structure. The regular measurement of structural deformation over a period of time (usually several years) will furnish information with regard to the general elastic behavior of the structure and its foundation, will provide a means for determining the elastic shape of the deflected structure permitting separation of the load and the thermal deflection components, and, with precise alignment data, will provide for determination of the amount of translational movement.

Plumblines commonly used to concrete dams normally consist of a heavy plumb bob suspended by wire either from near the top of the dam or an intermediate point in the upper portion of the structure. The plumblines are located in vertical wells usually formed in the maximum section and in section about midway between the abutments and the maximum section. Reading points are provided in one or more galleries in the lower portion of the structure and at other elevations if practicable, where the position of the plumbline with respect to the surrounding structure is observed by a micrometer scale or by optical devices.

Inclinometer-type devices have commonly been installed in embankment dams, foundations and abutments, and to some extent, in abutments and foundations of concrete dams. An inclinometer installation consists basically of a somewhat flexible grooved-wall casing constructed of plastic or aluminum and a device capable of electronically measuring horizontal deflection of the casing. The inclinometer device is lowered into the casing in sets of grooves at various time intervals during the construction and later usage of the dam. Comparison of horizontal deflection readings at various depths within the casing at different time intervals in the life of the structure will not only indicate the amount and time rate of movement, but the elevation at which it occurs. Inclinometer casing installations with slip-joint couplings also enable the determination of relative and total settlement of embankment dams.

Measurements of vertical movements such as settlement or heave may be accomplished by precise surveying (levelling) techniques or through use of specialized devices vertically arrayed including inclinometer casings with slip-joint couplings, settlement plates, crossarms, mechanical or electrical sounding devices, and borehole extensometers. Special horizontal systems that measure vertical movement include fluid levelling devices.

Total settlement and/or heave can readily be determined by the observation of marker points on a dam with reference to monument points located off the dam. Differences in elevation which occur with elapsing time are readily determined. It is obviously important to determine the initial elevation of the measurement points with great accuracy so that they will constitute a base reference to which future elevation determinations may be compared.

Similarly, most of the other vertical movement measuring devices also require very accurate determination of the initial elevation of the top or bottom of the installation to enable later comparative movements to be determined. This is true of slip-joint inclinometer casings where both top and bottom elevations are obtained, settlement plates where initial elevation of the plate surface is obtained, and other devices where one or more point elevations are determined not only at the time of installation, but at each additional reading interval.

B. Rotational Movements

The detection and quantification of rotational movements may be accomplished through evaluation of translational movement data or by use of specialized instrumentation (such as tiltmeters) at either embankment or concrete dams. If vertical and horizontal translational movement data are available at a number of locations at a dam, rotational movement may be determined by analyzing the relative translational movement at measurement locations along planes perpendicular to the axis of the dam. Data generated by two or more inclinometer installations along such a plane is especially adaptable to detection of rotational movement.

Tilt angles yielding rotational information may be obtained directly from devices such as tiltmeters which are installed on surfaces of concrete monoliths of concrete dams and on surfaces of concrete appurtenant structures on embankment dams.

C. Relative Movements

Relative movements of one portion of a concrete dam or concrete structure with respect to another portion of the dam or foundation are commonly measured by several types of strain detection devices. Such devices include jointmeters, extensometers, and several varieties of crack monitoring devices. The operation of these devices ranges from simple observation of relative movement using a micrometer, dial gauge, or a precision tape to measure between two fixed points to observation of electrical resistance changes in strain gauges or deformation gauges. Jointmeters are electrically operated, while extensometers and crack measuring devices are generally read manually. Jointmeters are normally embedded within the dam matrix, while extensometers and crack measuring devices are normally affixed to surfaces.

An indication of relative vertical movement in an embankment dam may be obtained from readings of relative settlement at various levels. Also, multiposition borehole extensometers are used for vertical or horizontal movement purposes, as are electrically operated shear strip devices which detect the location of relative movement upon failure of the device when installed in boreholes or affixed to appurtenant structures or geologic discontinuities. The relative movement of the concrete face or concrete-faced embankment dams is measured with jointmeters, slope inclinometers, and survey methods.

3.3. GROUND-WATER AND PORE-WATER PRESSURES

Ground-water level observations are commonly obtained at damsites before, during, and after construction to aid in the design of a dam, aid in determination of construction techniques, and to monitor effects of the reservoir on its surroundings. The observations may be made by simple open standpipes or wells or by piezometer systems of either the open or closed variety. In some instances, it is desirable to provide a sufficiently large observation pipe to enable pumping or bailing of ground-water samples for water quality testing purposes.

Pore-water pressure determinations are generally considered to represent information vital to the monitoring of performance of a dam both during construction and later operation. During construction, excessive pore-water pressures may signal a need for modification of construction procedures; while during operation, the porewater pressures may result in loss of embankment material strength, excessive uplift pressures on the base of a dam, or indicate excessive seepage through, under, or around a dam.

The hydrostatic pressure differential between the reservoir level and the downstream pool results in an obvious potential for seepage at every dam. Such seepage at an embankment dam is monitored by piezometric determination of phreatic levels at various locations in the dam, foundation, and abutments. In a concrete dam, seepage occurs through joints or cracks in the dam and through joints, cracks, or bedding planes in the dam foundation and abutments. Measurement of these pressures is important because of possible piping or other-seepage-induced instability situations.

A multitude of styles and types of pore-water pressure measuring devices have been available for use over the years. The basic types in use are piezometers which operate either as an open system or as a closed system. Open system piezometers include observation wells and standpipe piezometers. These devices allow water to enter into the standpipe through a strategically placed screen, a porous tube, or perforations in the pipes, the water level in the pipe is then measured by some suitable device.

Closed system piezometers include those which operate by hydraulic or pneumatic pressure balancing, those which read pressure directly by Bourdon-type gauges, and those read by electronically reading resistance strain gauges or vibrating wires. Each of the devices will read negative pore pressures. All closed system piezometers must be calibrated prior to installation or at the time of installation. Obviously, pore-water pressures are obtained only at the location of the piezometer tip or inlet, therefore, proper and judicious placement of piezometers is of extreme importance.

3.4. SEEPAGE

Seepage through, around, or below a dam is an extremely valuable indicator of the condition and continuing level of performance of the dam. The quantity of seepage existing at springs or entering a seepage collection system is normally directly related to the level of water in the reservoir. Any sudden change in the quantity of seepage collected without a correspondingly obvious cause such as an appropriate change in the reservoir level or heavy rainfall could signal a seepage problem.

Similarly, should the seepage water become cloudy, discolored, contain increasing quantities of sediment, or change radically in chemical content, a serious seepage problem could likely be indicated. Wet spots or seepage appearing at new or unplanned locations at the abutments, downstream slope, or downstream from a dam could be also indicate a seepage problem.

Commonly used seepage monitoring devices include quantitative devices for measuring seepage including weirs, flowmeter, Parshall flumes, and calibrated containers. Geophysical methods used for qualitative seepage analysis include thermotic surveys and self-potential measurements.

Weirs are one of the oldest, simplest, and most reliable devices that can be used for measuring quantity flow of water. The critical parts of weirs can be easily inspected, and any improper operations can be easily detected and quickly corrected. Weirs normally used are of the 90° V-notch, rectangular, or trapezoidal types. The quantity discharge rates are determined by measuring the vertical distance from the crest of the overflow portion of the weir to the water surface in the pool upstream from the crest. The discharge may then be computed by the appropriate formula or by reference to tables prepared for that purpose. Weirs can be installed in the drainage gutters of the galleries and adits of a concrete gravity or arch dam and in the channels or collector boxes in seepage collection systems.

A Parshall flume is a specially shaped open-channel flow section. The discharge may be computed or determined by reference to tables and charts prepared with throat width of flume, upstream head, and downstream head, and downstream head as variables.

Calibrated containers may be used to measure low flow quantities from a pipe outlet. The time required to fill a container is measured and the flow is computed.

Flowmeters and pressure transducer devices are sometimes used to determine quantity of flow in a pipe or open channel.

3.5. STRAIN MEASURING INSTRUMENTS

Strainmeters are embedded in concrete dams to provide data on strains, which when processed to exclude the creep strain effects, yield elastic stresses at the instrument location. Carlson elastic wire type strainmeter, which is a dual-purpose instrument as it measures temperature also, is the most commonly used in the United States. Strainmeters are installed in clusters of 7, 9 or 12 meters in three-dimensional configurations for determination of multi-dimensional stress at the cluster location. The clusters are located at several positions on a horizontal gageline at the centerline and near the base of the maximum section of the dam. For dams of unusual size, similar installations are made along horizontal gagelines at mid-height and at same elevations at locations near each abutment. The locations of interest are indicated by results of the theoretical stress analysis and any other special structural considerations.

3.6. STRESS MEASURING DEVICES

In many instances, it is desirable to known the state of stress between a dam and its abutments or foundations or between components of a dam. Stresses which were computed or accounted for in the design of a dam based on design assumptions may or may not actually occur in a completed dam. Therefore, certain instruments are utilized to determine the magnitude of the actual stresses at selected locations.

A number of types of pressure or stress measuring devices exist. Some devices measure strain which is then converted to stress by computational methods. Commonly used stress measuring devices include the Gloetzl flat plate, Carlson stressmeter, and the Goodman flat jack. The Gloetzl plate and the Goodman flat jack operate hydraulically to balance (null) a given pressure, while the Carlson stressmeter utilizes changing electrical resistance due to elastic wire length changes caused by applied pressure. Carlson stressmeters are usually embedded in the vicinity of strainmeters groups for measuring compressive stresses directly, thereby providing a check of stresses indicated by strainmeter data. Earth pressure cells are also used in embankments to measure the total earth pressure within the embankment or acting on concrete structures.

3.7. TEMPERATURE MEASUREMENTS

Temperature measurements are commonly made as a necessary adjunct to electrically obtained stress, pressure, and strain measurements to account for temperature change effects. It is obviously necessary to know the temperature of a vibrating wire or resistance strain gauge so that the temperature variable may be eliminated by reference to calibration charts.

Similarly, temperature measurements, both ambient and internal, are of great significance in the analysis of stresses in concrete dams. Mass concrete is especially subject to temperature induced stresses caused by expansion and contraction when the faces of the dam are in direct sunlight in warm weather or in the presence of very cold wind chill conditions. Reservoir water temperature on one side of an arch dam, for example, may be relatively quite warm compared to a very cold wind chill on the downstream face of the dam.

It has been noted that, in many cases, temperature induced strains and associated stresses may exceed those induced by reservoir load and other loads.

For temperature measurements in the interior of concrete dams for monitoring temperature distributions both during construction and service operation, Carlson type resistance thermometers are commonly embedded, generally, in a 50′ × 50′grid pattern in the maximum block and in two abutment blocks. The upstream face thermometers are installed flush with the face for monitoring reservoir water temperature at various depths.

3.8. SEISMIC EFFECTS

Seismic devices (seismographs) are used on both concrete and embankment dams in order to monitor the effects of both natural vibrations (earthquakes) and man-made vibrations (blasting). Such vibrations could result in excessive deformation or possibly liquefaction on an embankment dam or its foundation and an accompanying drastic reduction in structural safety. In a concrete dam, excessive vibrations could result in cracking, leading to severe defects in structural safety and increased seepage. Earthquakes may also lead to instability of abutments or reservoir slopes.

Most seismic instrumentation are primarily strong-motion devices (strong-motion accelerographs) which measure ground acceleration in two or more planes. These devices involve an embedded base in the portion of the dam to be measured and an accelerometer or other motion detection devices that record the magnitude of vibration as a permanent record over a given period of time. Some devices are continuously in operation, while others require a slight vibration to initiate operation. Generally, a seismograph is located in the vicinity of the base and/or abutment and the crest of the dam to record the ground motion and the response motion, respectively.

Detailed description of the various types of instruments for recording seismic effects, and considerations regarding their location and layout in dams is presented in the report titled " Seismic Instrumentation in Dams ", USCOLD Committee on Earthquakes, April 1975, and " Guidelines for Selection and Installation of Strong-Motion Instrumentation ", USCOLD Committee on Earthquakes, 1986.

The primary value of seismic data to dam designers is that recorded data can be used to determine whether actual response of structures to earthquakes are within design limits and whether the actual response conforms to that assumed for the structure.

3.9. ILLUSTRATIVE EXAMPLES

Table 3-1 lists the type and number of various types of instruments installed in some existing US concrete and embankment dams typical for these dam types.

Figures 3-1 through 3-7 illustrate typical structural behavior measuring instrumentation provided in the dam. Figures 3-1 through 3-4 illustrate performance monitoring instrumentation generally provided in concrete arch and gravity dams; New Bullards Bar and Morrow Point being representative arch dams and Glen Canyon high arch-gravity and Galesville, a roller-compacted concrete gravity dam.

Figures 3-5 through 3-7 for Oroville, Trinity, and Carter Dams illustrate dam behavior monitoring instrumentation typical for embankment dams.

3.10. NEW MEASUREMENT METHODS

This section presents brief information regarding the advances in deformation measurements by geodetic methods applying the latest equipment and mensuration techniques and new geophysical methods for monitoring seepage developed since the publication of ICOLD Bulletin No. 23 (July 1972). The geophysical methods include the Streaming Potential Method and Thermotic Monitoring Method for monitoring seepage.

A. Geodetic Methods

The text and plates of Part II of ICOLD Bulletin No. 23 describe the application of geodetic methods to determine the movements of dams. Information concerning the use of " Electronic Distance Measured Equipment " (EDME) and methodology for precision measurement of dam movements by applying trilateral mensuration is herein briefly presented.

The basic requirements of the EDME are as follows : 1) Calibration and Use of Distance Measuring Equipment; 2) Instrument Error Source; and 3) External Error Sources — *a)* Meteorologic Correction, *b)* Control Monument Network, *c)* Target Retro-reflectors Pedestals, and *d)* Forced Centered Mounting.

The establishment and maintenance of the control monument network cannot be overemphasized. The site or location for the control monuments must be chosen in relationship to the structures to be measured, away from the dam to minimize the influence of variation due to impoundment or structure movements. The criterion for location of monument sites is to form a " braced quadrilateral ". Installation of the " target retro-reflector pedestals " require visibility from two or more control monuments to establish the initial distance or location and to determine occurrence of movement during subsequent measurements.

The last requirement for ensuring precise mensuration is the physical mounting of the (EDME) to the control monuments and the mounting of retro-reflectors to the target pedestals. A system of " forced centered mountings " for both the (EDME) and the retro-reflectors assures the measurement regime necessary to minimize " system " errors and assures measurement repeatability of the distances during the initial measurement.

The final requirements for assuring precise measurements are : The PERSONNEL involved with measurements and PROCEDURE in the conduct of performing the measurement steps. It is imperative that an operational sequence plan be established for equipment start-up and warm-up period, initial test, and during the actual measurements.

B. Geophysical Methods

1. *Streaming Potential Method for Seepage Monitoring.* — This method is based on the phenomenon that water, low in dissolved solids, generates an electrical current when forced to flow under laminar conditions through porous earth materials, and has been used to investigate seepage loss from reservoirs. Usually, a geophysical type investigation using a portable electro-device is performed within the reservoir to detect the origins of seepage paths. Recently, the USBR and others have employed methods whereby fixed position electrodes have been used to detect streaming potentials downstream of reservoirs. The streaming potential, which relates one region of flow to another, will vary directly with the difference in flow velocity. Seepage monitoring procedure consists in placing a reference electrode in an area of minor seepage occurring. Areas where more seepage is occurring will have a negative electrical potential relative to reference area when positive terminal of the voltmeter is connected to the reference electrode.

2. *Subsurface Temperature Monitoring (Thermotic Monitoring).* — This technique is based on the effects of groundwater conditions on subsurface temperatures downstream from dams and abutments, and has applications for monitoring seepage at the dams. The methodology is based on the following principles. The ambient surface temperature at any site undergoes yearly cyclic changes. Generally, a constant temperature gradient with depth will be noted downstream from the dam and abutment. This will be affected significantly if reservoir water is entering these areas as subsurface seepage, causing observed heating and cooling. More direct response of a monitored subsurface point to fluctuations in the reservoir temperature is indicative of greater seepage rate between reservoir and that point. Instrumentation consists of thermotic probes, which are linear thermistor probes calibrated to ± 0.01 °C, that are installed at predetermined monitoring grid locations to a single uniform depth of usually 7 and 10 feet. Observed temperature data are then analyzed to determine seepage rates.

CHAPTER IV

INSTRUMENTATION SYSTEM DESIGN

4.1. INSTRUMENTATION SYSTEM DESIGN

The design of an instrumentation system to monitor the performance of a dam should be regarded as an integral part of the overall design of the dam. The instrumentation system design must be consistent with the design of all other project components. The same level of design effort intensity and care should be applied to the task of instrumentation system design as other design activities such as structural design, hydraulics, and foundation treatment. The design must be based on the geotechnical, hydraulic, and environmental conditions at the site and on their interaction with the structure. The extent and nature of the instrumentation depend on the type and complexity of the dam, the size of the impoundment, and the potential for adverse consequences such as loss of life and property damage if the performance of the dam does not meet the performance criteria. Instrumentation design is not merely the selection of instruments, but is a comprehensive engineering process that begins with defining the objective and ends with implementation of operational or analytical action based on the data. The design of the instrumentation system should consist of the following steps.

4.1.1. Define Project Conditions

Project conditions include project type, subsurface stratigraphy and engineering properties, groundwater conditions, environmental conditions, downstream risks to life or property, status of nearby structures or other facilities, and planned construction method.

4.1.2. Define Purpose of Instrumentation

The purpose of the instrumentation should be clearly established relative to the project conditions. The instrumentation could have the purpose of construction control, safety, diagnosing the specific nature of an adverse event, verifying design adequacy, proving adequacy of a construction technique, verifying long term satisfactory performance, verifying contractor compliance with specifications, advancing the state of the art, or legal reasons.

4.1.3. Select Variables to be Monitored

Variables to be monitored include groundwater level, pore water pressure, earth pressure, vertical and horizontal deformation, relative deformation, tilt, load, strain, temperature, vibration, reservoir and tailwater level, rainfall, and air and water temperature.

4.1.4. Make Predictions of Behavior

Predictions are necessary so that required instrument ranges and accuracies can be selected. Predictions also provide input to locating and orienting instruments used to measure pressure and deformations. If measurements are for the purposes of safety or construction control, numerical values should be determined for the parameters which, if attained, will require a remedial action plan to be implemented.

4.1.5. Devise Solutions to Problems that may be Disclosed by Observations

(Remedial Action Plan)

Inherent in the use of instrumentation is the absolute necessity for deciding, in advance, a positive means for solving problems that may be disclosed by the results of the observations. If the observations should demonstrate that the least favorable conditions compatible with the results of the design studies actually do prevail, the corresponding problems must be resolved with appropriate, previously anticipated solutions.

A list of instrumentation tasks for which responsibility must be assigned includes : instrument specifications, instrument procurement, instrument calibration, instrument installation, instrument monitoring, instrument maintenance, data processing, data analysis and interpretation, and implementation of remedial action plans. Completion of this list will identify any gaps in the assignment of responsibilities; if personnel are not available to complete these tasks, this may influence the direction of the entire monitoring program. The tasks assigned to the instrumentation specialist should be under the supervision of one individual. Task assignments should clearly indicate who has overall responsibility for implementing appropriate corrective action warranted by the results of the observations.

4.1.6. Select Instruments

The preceding six steps should be completed before instruments are selected. In the selection of instruments, the overriding desirable feature is reliability. Inherent in reliability is maximum simplicity, maximum durability in the installed environment, minimum sensitivity to climatic conditions, and a good past performance record. Components that will not be damaged by construction equipment, vandalism, water, dust, heat, or subsurface chemistry and that will survive deformation of the materials in which they are installed should be selected. Sensor, readout, and linkage between sensor and readout should be considered separately, as different criteria may apply to each.

The least expensive instrument may not result in minimum total cost. In evaluating the economics of alternative instruments, the total costs of procurement, calibration, installation, maintenance, monitoring, and data processing should be compared.

It is desirable that calibration can be verified after installation. The instrument should be consistent with the skills of the available personnel and, if limitations in future monitoring personnel are possible, automation capability should be carefully considered. There should be minimum interference to construction during installation and monitoring. Consider special needs for access while reading. An instrument should not by its presence change the variable it is measuring from that which would be measured if it were not there. Both construction and long term conditions of operation should be considered. The monitoring method should be selected to be compatible and efficient with the planned frequency and duration of readings. A course of action should be planned in case of system malfunction. Problems with installation, procurement, maintenance, and training should be considered. Finally, the instrument should achieve the stated objective of the measurement.

4.1.7. Plan Recording of Factors that may Influence Measured Data

Measurements by themselves are rarely sufficient to provide useful conclusions. The use of instrumentation entails relating measurements to causes, and therefore complete records must be maintained of all factors that might cause changes in the measured variables. Construction details, visual observations of behavior, temperature, snow and rainfall, reservoir level, tailwater level, spillway flows, and installation details of each instrument should be recorded.

4.1.8. Establish Procedures for Ensuring Reading Correctness

Personnel responsible for instrumentation should be able to answer the question : Is the instrument functioning correctly? Among the procedures for addressing this question are a simple visual means of checking for gross errors, a backup system, and periodic calibration and maintenance. Certain instruments are equipped with self-verification features whereby a reading can be verified in place; this feature is desirable.

4.1.9. Select Instrument Locations

The selection of instrument locations should reflect predicted behavior, especially for critical zones and critical construction stages. Locations should be selected so that data can be obtained as early as possible in the construction process. Flexibility should be maintained so that location plans can be changed as new information becomes available during construction. Recognizing the inherent variability of soil and rock, it is often worthwhile to instrument a few locations fully, and to use inexpensive " index " devices at these and many other locations to address the question : Are the fully instrumented locations representative of behavior? If the answer is no, it may be necessary to install additional instruments to define behavior adequately. The layout should provide cross-checks among instruments.

4.1.10. List Specific Purpose of Each Instrument

Each instrument indicated on the plans should be numbered and its purpose listed. If no viable specific purpose can be found for a planned instrument, it should be deleted.

4.1.11. Write Instrument Procurement Specifications

Attempts by users to design and manufacture instruments usually have not been successful. Therefore procurement specifications are needed. Specifications can be method type with model number, method type without model number, or performance type. Either the owner, or his design consultant, or the contractor can be responsible for procurement. Price can be determined by bid or negotiation.

4.1.12. Write Contractual Arrangements for Field Instrumentation Services

Contractual arrangements for the selection of personnel responsible for field instrument installation and data collection and interpretation may govern success or failure of a monitoring program. The following contractual arrangements are possible : field instrumentation services by owner's personnel; bid items in prime contract with no prequalification; bid items in prime contract with prequalification; instrumentation specialist selected by and contracting with owner; and instrumentation specialist selected by owner and contracting with construction contractor.

4.1.13. Plan Installation

Installation procedures should be planned well in advance of scheduled installation dates. Written step-by-step procedures should be prepared, making use of the manufacturer's instruction manual and the designer's knowledge of specific site needs. The written procedures should include a detailed listing of required materials and tools and should provide for alternative methods in the event that problems arise in the field, such as inability to maintain an open borehole with drilling fluid or unanticipated subsurface stratigraphy. The fact that the owner's personnel will install the instruments does not eliminate the need for written procedures. Installation record sheets should be prepared. Plans should be coordinated with the contractor and arrangements made to protect installed instruments from damage caused by construction activities and vandalism.

4.1.14. Plan Procedures Subsequent to Installation

General guidelines for instrument calibration and maintenance and for data collection, processing, and interpretation are given by Dunnicliff (1982). Data sheets should be prepared at this stage. All parties should be forewarned of the planned means of solving any problems that may be disclosed as a result of the observations.

CHAPTER V

MONITORING FREQUENCIES

5.1. GENERAL CONSIDERATIONS

The observation schedule which indicates the monitoring frequencies to be followed must address the four basic stages of the life of a dam.

1. Pre-construction - observations made during this stage are primarily made to provide baseline data for comparison with measurements made in later stages.

2. During construction - observations either identify problems or verify that structural behavior is compatible with expectations.

3. During first filling - monitoring frequency is normally the greatest during this critical stage. Observations provide a means to evaluate design assumptions, construction adequacy, and overall performance.

4. During service operation - observations are made on a less frequent basis. They serve as confirmation of continued acceptable behavior or provide warning of potential problems. Frequencies should be increased when abnormalities are noted and until the cause is detected and corrected. Frequencies should be greater during rapid or frequent changes in reservoir or tailwater level or during very high reservoir stages (flood) and following strong earthquake shaking.

It is impractical as well as inadvisable to prescribe a predetermined, inflexible observation schedule which would have universal application. The observation frequency must be adequate during construction and first filling to determine the time rates of change of measured quantities, taking into consideration the accuracy of the measurements. The anticipated schedule must be predicated on site specific geotechnical and geophysical factors, taking into consideration applicable requirements by the regulatory agencies. The schedule must be intentionally flexible with automatic alternative courses of action to react to :

- changes in anticipated site conditions,
- changes in construction procedures,
- changes in design or regulatory requirements,
- unexpected or unusually severe natural phenomena.

5.2. OBSERVATION SCHEDULE

The following schedules provide a basic framework from which to formulate a site specific monitoring schedule compatible with the types of instruments installed and the particular requirements of the project.

A. Pre-Construction Observations

- Geodetic - once before start of construction.
- Groundwater levels - once before start of construction.
- Seismic activity - early before construction to establish reference base.

B. Schedule During Construction, First Filling, and Service Operation

This schedule is indicated in Table 5-1.

CHAPTER VI

DATA COLLECTION, REDUCTION AND PRESENTATION

6.1. GENERAL

Considerations concerning data acquisition, processing and presentation of results, including requirements for instrumentation personnel responsible for these tasks, are described in this section. Data acquisition required by the schedule is accomplished either manually or by automated system, depending on the instrumentation system provided in the dam. Requirements for record of field readings, need for prompt and prioritized data processing in accordance with applicable analysis procedures, sources of errors, and requirements for presentation of results of data analysis in terms of measurement or response values for use in interpretation and evaluation of dam performance are presented.

6.2. DATA COLLECTION

6.2.1. Instrument Observations

Readings are taken manually or by automated data acquisition system, depending on project instrumentation system and strictly in accordance with applicable procedures and instrument manufacturer's instructions. Readings should be made at regular intervals in accordance with the established observation schedule for various instruments. Careful attention should be exercised in taking readings to ensure greatest accuracy and reliability of the observed data consistent with particular instrumentation system. The reading equipment (test set, etc.) should be checked to ensure its proper functioning before start of each new set of readings and repaired if warranted.

Readings from the instruments should be recorded on specially prepared field data forms. Previous readings should be available for immediate comparison so that changes can be verified as real or erroneous caused by misreading or malfunction of the readout unit or sensor. Repeat readings should be taken in case first readings appear unusual or doubtful but should be recorded along with the first reading. Any unusual construction activities or other information (such as air temperature, reservoir level, precipitation; weather condition, wind, etc.) that might affect the data should be noted on the data form.

With the advent of low cost microcomputers, consideration of their use for data acquisition is an obvious choice, particularly in those cases where large quantities of data have to be dealt with. Microcomputers can also be used at the project site to link up with an off-site larger computer for data storage and further data analysis and plotting. Manual reading of individual instruments is the practice in use in the majority of cases. However, recent advances in electronics, particularly in the miniaturization of processors and sensors, increased performance reliability, and decreasing cost of these devices will undoubtedly change data acquisition and processing techniques.

To enable a better assessment of instrument performance and to increase the confidence in the readings, instruments with different types of sensors should be installed close to each other (i.e., flushable hydraulic cells, along with vibrating wire instruments in the case of piezometer installations). This practice would facilitate periodic checks and improve the reliability of the readings.

6.2.2. Instrumentation Personnel

The readings should be carried out by instrumentation personnel who are thoroughly experienced, motivated and capable, and fully understand the purpose and importance of instrumentation. This group should be headed by a senior civil engineer who is intimately familiar with the instrumentation system, project structures, and their structural performance characteristics. His responsibility should also include preliminary interpretation of the readings obtained and to determine their significance and to alert responsible parties (owner and engineer) if such evaluation indicated cause for concern.

Federal agencies, such as US Bureau of Reclamation, US Army Corps of Engineers, and some large utilities who own and operate many dams, have well-organized in-house instrumentation and dam performance evaluation groups staffed with experienced engineering personnel. These groups have responsibilities for instrumentation, data collection and review, data reduction, presentation and interpretation of results, and evaluation of dam performance. However, smaller utility companies or municipal entities who own and operate dams may not have in-house engineering capabilities and staff to form their own instrumentation and performance evaluation groups. Although such owners have intelligent, motivated personnel who can read the instruments, they must rely on the services of another engineering organization of consultants (frequently not close to the site) for review and reduction of data, presentation of results, and performance evaluation.

6.2.3. Sources of Errors

Common sources of errors are associated, in the case of electric type sensors, with drift in their zero calibration, change in resistance due to temperature effects, and leakage between conductors. These effects may be significant in reducing the accuracy of the instrument readings where leads are very long. In the case of pneumatic instruments, errors in the readings may be introduced if the air or gas flow to balance the diaphragm is applied too fast or supplied at too high pressure. The latter may cause damage to the diaphragm, creating an error in the readings. It has also been found that the readings of these particular instruments may be subject to operator reading methodology.

It is mandatory to evaluate early during construction and to confirm later during operation of the project the accuracy and reliability of the instruments installed and readout units used to obtain the readings. An overall review of the results and assessment of their validity will be necessary to ascertain errors due to instrument shifts, possible random errors and other disturbances introduced during installation (especially for installation of total pressure cells where local arching is very common), and to distinguish them from real trends.

6.3. DATA REDUCTION

Observed instrument data should be processed promptly to provide information on measurements or response quantities for evaluation of dam performance. Promptness in data reduction cannot be overemphasized. Stacking of field reading forms without further necessary data processing or processing considerably much later, negates the very primary purpose of instrumentation. The promptness in data reduction will, in great part, depend on the amount of data to be processed and adequately plotted. The volume of data will be directly related to the frequency of reading and extent of the instrument system. When many frequent routine readings are to be taken, such as during the filling of the reservoir, the processing of data should be carried out on a priority basis. Prioritization will depend on relative importance of the various types of measurements. Thus, during the first reservoir filling, information concerning dam displacement, settlement, deflection, seepage, uplift, and leakage are of the utmost importance for control. Processing of data should therefore be according to selected instruments. The selection will depend on the function and location of the instruments, the redundancy available, and type of structure. The selection procedure should be based on the instrumentation monitoring program, which requires a thorough understanding of the parameters measured and their influence on the safety of the structure.

The data processing should comprise the following stages :

1. Reduction of readout readings into meaningful measurement values.

2. Scanning of selected readings to detect any sudden change or to confirm unusual trends that may require immediate action, or to pinpoint a potential deficiency.

3. Summary and presentation in tabular and graphical forms, the necessary data for the safety monitoring of the project, and comparison of observed with predicted behavior.

4. Storing of all information in a data bank for future reference and analysis if and when problems develop.

If computer methods are not used, reduction of data should be carried out on calculation forms specially made for each instrument. Formulas used to reduce the data, including calibration constants and correction factors, should be included on the forms.

Summary sheets should contain the final measurement values, together with the date, time of reading, and instrument name, number and/or code. A column reserved for observations or remarks should also be included on this sheet.

6.4. DATA PRESENTATION

Graphical presentation of the results of instrument data analysis in terms of measured values of response parameters should be considered as one of the key end products of data processing. It should be the principal aid for the interpretation of the results of instrument data analysis and for performance evaluation of the structures. The plots should be prepared using reasonable scales, which should be made standard to all graphs so that comparisons can readily be made with response values, observed at other times or at other comparable locations.

Graphical presentation of the history of measured values of response parameters (e.g., dam deflection, seepage, uplift, etc.) by plotting values of parameter on time base provide direct indications of trends and pattern of its variation with time. Plots of corresponding values of reservoir level, air temperature, or any other pertinent loading parameter on the same sheet with plot of the response parameter, facilitates direct correlation of the response with corresponding operating loading conditions and realistic evaluation of the performance of the structure. Figure 6-1 shows a typical stress history plot together with corresponding reservoir level, air temperature, concrete temperature, and construction progress. The response values could also be presented in the form of other useful plots (e.g., response value versus reservoir level, tailwater level, seepage, etc.) to study relationship of interest for comparison with theoretically predicted performance values.

CHAPTER VII

PERFORMANCE EVALUATION

7.1. GENERAL

The structural performance evaluation of a dam and its foundation is to be based on results of the monitored instrumentation data analysis expressed in terms of the values of various response parameters; for example, dam displacement, settlement, foundation deformation, stresses, seepage, uplift pressure, etc. The performance assessment involves correlation of response quantities with corresponding operating loading conditions, determination of variation trends, and careful comparison of the measured response quantities with those predicted theoretically and/or experimentally for comparable loading conditions. For this purpose, complete information must be readily available concerning loading and response values expressed both in tabular form and history plots of each response parameter, and related applicable loading such as reservoir water level, tailwater level, air temperature, and construction progress. In addition, information concerning design assumptions and theoretically determined " acceptable tolerance " limit or range for each response parameter must be available.

7.2. PERFORMANCE EVALUATION

The detailed evaluation of performance from results of instrumentation data analysis and the comparison of such performance with design assumptions should obviously be made by experienced engineering personnel familiar with :

- The purpose of the overall instrumentation scheme.
- The physical tolerances and limitations of the instruments themselves.
- The expected performance of the structures under scrutiny.
- The impact of out-of-tolerance readings.

Any evaluation of data conducted without benefit of all of the above will likely result in inaccurate conclusions and improper reactions.

The detailed evaluation and interpretation of results of all instrumentation data analysis should be undertaken immediately if maximum benefit is to be derived from the process. Probably the most common and least excusable deficiency suffered by contemporary performance evaluation programs is one where data lie uninterpreted until, at some point in time, they are rendered obsolete by more current data. If the physical instrumentation systems are justified, then timely maintenance, observation, and data analysis and performance evaluation are equally justified.

The actual process of evaluating instrumentation data and comparing such data with design assumptions must be, to a degree, unique to the project in question if it is to best address the individual concerns and questions generated by the project. For example, correlating certain types of instrumentation data may, for a particular structure or site, require consideration of the effects of " time lag ". On the other hand, there are several principles, processes, and situations which should be considered in the evaluation of any data set. For example :

1. Plots of data versus time and plots of data on plan or sectional views of affected structures lend to meaningful interpretation.
2. Distorted scales often lead to distorted interpretations and conclusions.
3. All " glitches ", even mistakes, in the data have a logical explanation. It is, however, contingent on whether or not the engineer has the time, patience, experience, and budget to arrive at the explanation. Availability of complementary construction and operation information is often a determining factor.
4. Conclusions should generally be based on trends established over some reasonable period of time.
5. Correlations of different types of data should be made to ascertain reliability of monitored performance.
6. All instruments have limitations. Data yielded at points beyond such limits are of questionable value. Likewise, attempts to evaluate data, the magnitude of which lies within the margin of error, will be unproductive.
7. All structures and foundations demonstrate a " tolerance " for certain magnitudes of displacement, pressure, etc. Accordingly, acceptable limits of performance should be established for all affected project features prior to initiation of instrumentation evaluation. This will assure that such criteria are rooted in engineering logic, not panic.
8. All instrumentation programs should have a predetermined " life-need ". Instruments that have fulfilled their purposes should not be read. Often, they only contribute to an accumulated volume of paper and obscure valuable data.

One must always remember that instrumentation data which deviates from assumed acceptable levels does not absolutely mean that problems exist; likewise, data which lie within the acceptable range do not guarantee that no problems exist.

When instrumentation data have been collected and analyzed and structural performance has been accordingly evaluated, decisions must be made as to what action, if any, is dictated by the conclusions of the analysis. These decisions should be soundly based on responsible engineering logic and not on emotional reaction. Engineers responsible to establish a plan, schedule, and accomplish any required remedial work must assure that :

- The schedule is expeditious, but not unnecessarily compressed.
- The plan is scoped to adequately address the problem identified without unnecessary " frills ".
- Adequate attention is given to the continued observation, maintenance, and evaluation of instrumentation during and after the period of remedial work.

Unfortunately, proper response to engineering reevaluation is all too often hindered by a designer's or owner's failure to maintain a balanced sense of responsibility. Owners may tend to minimize the magnitude and/or urgency of the problem opting for the less expensive or " do nothing " approach if during construction the possibility of contractor's claims of delay and associated extra cost is a great factor. The original designer, possibly " ego-involved " with the original design, also is often tempted to minimize the problem. On the other hand, engineers and consultants entering the picture later may, for any number of reasons, feel compelled to the other extreme. The objective is to give prudent attention to all concerns, ranging from hazard to economics. In the final analysis, the action to be taken will often be dictated by the hazard potential represented by the structure in question. In any event, it is the engineer's responsibility to assure that the three noted objectives are met without compromise of the types mentioned above.

It would be impossible to over-emphasize the importance of engineering experience in the area of performance evaluation. It should be obvious that the quality of the observations, evaluations, and consequential conclusions will be proportional to the qualifications, experience, and dedication of the personnel assigned to the various tasks. Even the most menial work items are critical. It is with this understanding that the prudent manager conveys to each staff member the essential nature of each phase of the observation and evaluation program. It is with this understanding that all personnel are encouraged to continually use their minds and eyes, realizing that the success or failure of the program is critically dependent upon each and every individual involved.

The report herein was developed by the Measurements Committee, United States Committee on Large Dams. The list of Committee's members comprise representation from private individuals, industry, educational institutions, and governmental agencies. The members are involved in consultation and the design, construction, or operation of water resources projects including inspections and evaluation.

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Special thanks are extended to this group for their efforts and contribution in the report preparation.

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APPENDIX A

AUTOMATED DATA ACQUISITION

A.1. INTRODUCTION

Automation of data collection in dams is increasingly used for a variety of reasons. Chief among these is the greatly decreased cost of automated monitoring systems, the increased reliability of these systems, greater availability of electronic sensors for making measurements and the increased cost of labor for monitoring.

This section provides a guide to some of the factors affecting one's choice of an automated system for a dam. With the rapid evolution of electronic equipment now in process, references to specific hardware will no doubt be obsolete in some portions before publication. However the basic principles of automation should remain applicable for some time.

A.2. PURPOSE OF AUTOMATING DATA COLLECTION

Considerations and reasons for automating the data collection system for structural performance monitoring instrumentation in a dam include one or more of the following :

- Decreases labor required to measure, reduce and portray data.
- Decreases elapsed time between measuring data and interpreting data.
- Provides automatic warning if limiting values for readings are exceeded.
- Allows more frequent readings without increased cost to help isolate spurious readings.
- Transmits data to another location for evaluation.
- Decreases errors in data collection and reduction.
- Enables continuous long-term collection of data at the required intervals.
- Enables direct feeding of data into a computer database for interpretation and production of charts.

A.3. COMPONENTS OF A TYPICAL DATA ACQUISITION SYSTEM

1. Transducer; 2. Signal conditioner; 3. Analog-to-digital converter, digital-to-analog converter, binary coded decimal converter, frequency and voltage converters, etc.; 4. Microprocessor to control data collection and storage; 5. Storage

medium (memory, diskette, tape, printer); 6. Monitor; 7. Printer; 8. Plotter; 9. Communications equipment; and 10. Protection against transient voltage such as lightening, RF, etc., at power, sensor, and all other avenues of input.

A.4. SOME FACTORS TO CONSIDER IN SYSTEM SELECTION

1. *Number of Sensors* - Number of sensors dictates the number of channels which the analog unit must handle. This directly affects the cost of the system.

2. *Frequency of Readings* - Frequency of readings and number of channels affects the speed with which the unit must sample. Sampling speeds greater than a few channels per second usually require more expensive equipment and limit the amount of real time data processing that can be performed on the measurements.

3. *Required Accuracy of Readings* - Resolution of the analog-to-digital conversion unit, electrical noise, voltage losses in the sensor lines, and calibration errors affect the accuracy of readings. Resolution of the unit is an important factor affecting the design of the overall data acquisition system. Systems are available with 8, 10, 12, 14, and 16 bit resolution. A 12 bit system can read data to 1 part in 2 raised to the power of twelve or 1 part in 4 096. If the range of the unit is 10 volts, then the most accurate reading possible with the unit is 0.0024 volt. Such a unit would not be appropriate to read the output of a thermocouple. Systems with higher resolution tend to be more expensive and collect data more slowly.

4. *Range of Readings* - Range of readings is controlled by one's choice of sensors and the actual values those sensors may encounter. Range is the difference between the maximum and minimum output the sensor is designed to give. Range and resolution together with signal outputs of the sensors must be considered together when selecting a data acquisition system. For example a system with 12 bit resolution and a range of 10 volts would not be satisfactory to read the millivolt output of a thermocouple. However it might be quite satisfactory to read the output of a joint meter with 0.5 inch of travel to a resolution of 0.0001 inch.

5. *Period for On-Line Data Storage* - This affects the size of the data storage unit and overall cost of the system.

6. Distance from Sensors to Computer; 7. Output of Sensors (voltage or frequency); 8. Method of Data Transfer to Central Office; 9. Criteria for Evaluating Readings; 10. Procedures to Identify, Isolate and Remove Spurious Readings; 11. Electrical Isolation of Measuring System; 12. Reliability of System Components; 13. Procedures to Manually Check Results; 14. Availability of Service for Equipment; and 15. Need for Emergency Backup.

A.5. READINGS WHICH CAN BE USED IN AUTOMATED SYSTEM

- Vertical movement (strain); extensometer, settlement point.
- Horizontal movement (strain); plumbline, inplace inclinometer.
- Relative movement (strain); extensometer, joint meter.
- Temperature; thermocouple, thermistor, RTD.
- Stress; earth pressure cell.

- Tilt.
- Seismic; displacement, velocity, acceleration.
- Pore pressure; water level indicator in well, pneumatic piezometer, pressure transducer.
- Seepage; flow meter, flume, weir.

A.6. REPRESENTATIVE DAMS CONTAINING AUTOMATED SYSTEMS

Automated data acquisition systems have been provided at some dams. These include dams with automated systems owned by the US Bureau of Reclamation (USBR) and also those owned by others. Figure A-1 illustrates such a system.

USBR Concrete Arch Dams

Monticello Dam, California; Glen Canyon Dam, Arizona; Flaming Gorge Dam, Utah; Morrow Point Dam, Colorado; Crystal Dam, Colorado.

Other

Bath County Pumped Storage Project, Upper Dam and Lower Dam, Virginia (earthfill/rockfill).

The following dams will be equipped with automated systems : Yellowtail Dam. Montana (concrete arch); Ridgeway Dam, Colorado (earthfill); Navajo Dam, New Mexico (earthfill); Calamus Dam, Nebraska (earthfill); San Justo Dam, California (earthfill); Lock and Dam 26 (concrete gravity on piling); Clarence Cannon Dam (earthfill/concrete spillway).

Automatic Monitoring Capabilities

Automatic monitoring capabilities provided or to be provided at the above-listed dams include the following :

Name of Dam	Capabilities*
Monticello	1, 3, 4, 13, 14, 15, 17, 18
Glen Canyon	1, 3, 4, 5-7, 13, 14, 17, 18
Flaming Gorge	1, 3, 4, 5, 7, 13, 14, 17, 18
Morrow Point	1, 2-4, 6, 13, 14, 16, 17-20
Crystal	1, 3, 4, 6, 13, 14, 17, 18, 20
Yellowtail	1, 3, 4, 5, 7, 13, 14, 16-20
Ridgeway	6, 7, 8, 10, 11, 13, 17, 19
Navajo	4, 6, 7, 13, 17-20
Calamus	7-9, 12, 13, 17-19
San Justo	4, 9, 13, 17-19
Clarence Cannon	7-9
Bath County Pumped Storage Project Dams	4, 8, 9, 13, 14

* 1. Plumblines.
2. Tiltmeters.
3. Carlson meters.
4. Weirs and flumes.
5. Uplift pressure monitoring.
6. Extensometers.
7. Open-standpipe piezometers or observation wells.
8. Pneumatic piezometers.
9. Vibrating-wire piezometers.
10. Pneumatic total pressure cells.
11. Vibrating-wire total pressure cells.
12. Pneumatic settlement sensors.
13. Reservoir water level.
14. Tailwater level.
15. Reservoir water temperature.
16. Landslide monitoring (settlement and inclination).
17. Automatic data transmission via satellite.
18. Data transmission on command via telephone.
19. Radio communication internally in the system.
20. Local voice-synthesized alarm messages via telephone.

TABLE 3-1

DAM MONITORING INSTRUMENTATION

A. CONCRETE DAMS

Name of Dam (Year Constructed)	Height/ Crest Length (meters)	INSTRUMENT TYPE Plumblines	Uplift Pressures	Collimation	Foundation Deformation	Emb. Insts. (Strain, Temp.)	Drain Flows	Seepage Measurement	Others
Crystal (1976)	98/194	16	-	3	16	28	54	13	Slide meas.; tape gauges
East Canyon (1966)	79/133	-	-	4	10	-	-	-	Triangulation
Flaming Gorge (1964)	153/392	24	13	8	-	1,078	-	15	16 thermometers
Grand Coulee Forebay (1974)	55/357	24	33	11	10	23	37	-	Whittemore pts; deflectometers; thermometers
Glen Canyon (1964)	216/476	25	38	-	12	1,800 +	16	-	Triangulation; climatological
Hungry Horse (1953)	172/645	12	50	-	-	464	139	-	Climatological
Monticello (1957)	93/312	6	-	-	-	162	-	-	EDM; triangulation
Morrow Point (1968)	143/221	26	-	5	3	1,118	36	-	Power plant mmts; slide monitoring
Nambe Falls (1976)	46/98	-	10	6	-	60	21	11	Emb. measurements; flatjack pressure (12)
Pueblo (1975)	58/3109	6	10	6	6	-	8	-	Buttress movement 12; EDM-20 Emb. measurements
Yellowtail (1966)	160/451	9	23	3	9	1,650 +	-	193	Obs. wells 45
Clarance Canon (1984)	138/1940	2	42	-	-	47	-	-	Trilateration 43 points
Dworshak (1973)	218/1000	2	55	52	9	790	-	4	Seismographs (4)
New Bullards Bar (1969)	193/716	4	18	-	39	518	-	15	Triangulation 13 points; jointmeters 172

TABLE 3-1 (cont'nd)

DAM MONITORING INSTRUMENTATION

B. EMBANKMENT DAMS

Name of Dam (Year Constructed)	Height/ Crest Length (meters)	INSTRUMENT TYPE						
		Pneumatic Piezometers	Standpipe Piezometers	Inclinometers	Vibrating-Wire Piezometers	Measurement Points	Seepage Measurement	Others
Calamus (1985)	29.3/2195	48	106	3	16	66	25	Baseplates 12; pneumatic settlement sensors 48; thermistors 111
Choke Canyon (1982)	43.1/5631.4	none	53	none	-	96	none	Baseplates 7
McGee Creek (under construction)	50.0/600	77	41	7	-	57	none	Pneumatic settlement sensors 8; total pressure cells 24
McPhee (1984)	82.3/396.3	96	22	7	-	40	none	Pneumatic settlement sensors 64; extensometers 2; strong motion 5
Navajo (1963)	123/1112	none	48	none	-	60	7	Hydraulic piezometers 40; internal vertical movements 2; water analysis 11; horizontal drain 3
Palmetto Bend (1980)	21/13,904	none	60	4	-	3	128	
Red Fleet (1980)	44/518	27	38	9	-	70	2	Horizontal drains 100; tunnel drains 30
Ridgeway (under construction)	69.2/740.9	68	53	14	8	86	2	Total pressure cells 13; extensometers 16; strong motion 6
San Justo (under construction)	43/220.1	none	30	23	32	100	15	
San Luis (1967)	116/5669	none	61	19	70	250	13	Hydraulic piezometers 119; internal vertical movements 4; baseplates 3
Sugar Pine (1980)	58/183	21	4	5	-	20	1	Hydraulic piezometers 30; total pressure cells 29; extensometers 12; internal vertical movements 1
Clarence Canon	-	62	20	9	21	28	-	Carlson soil pressure cell 1; Carlson electrical piezometers 5

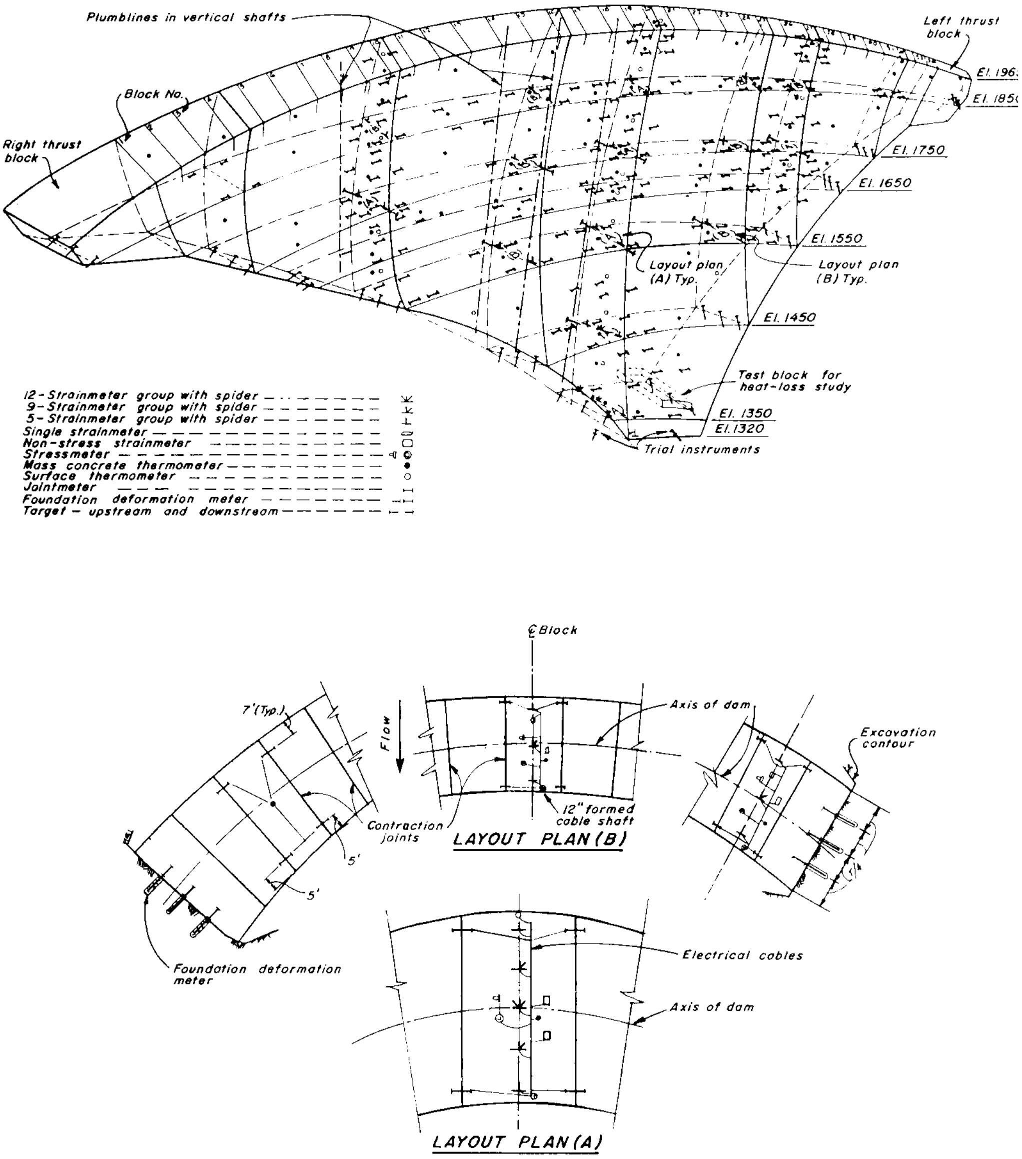


Figure 3-1. New Bullards Bar Dam.

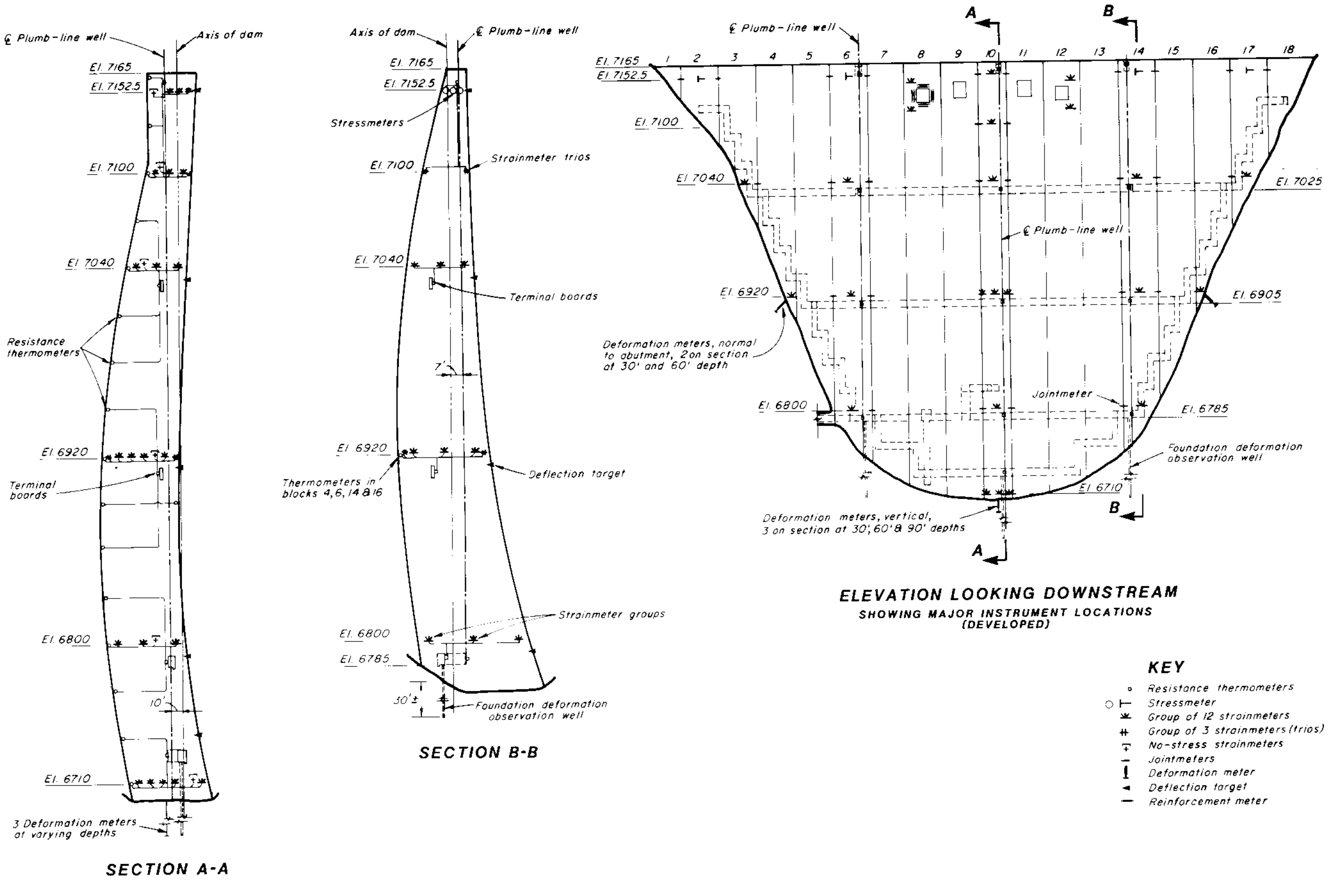


Figure 3-2. Morrow Point Dam

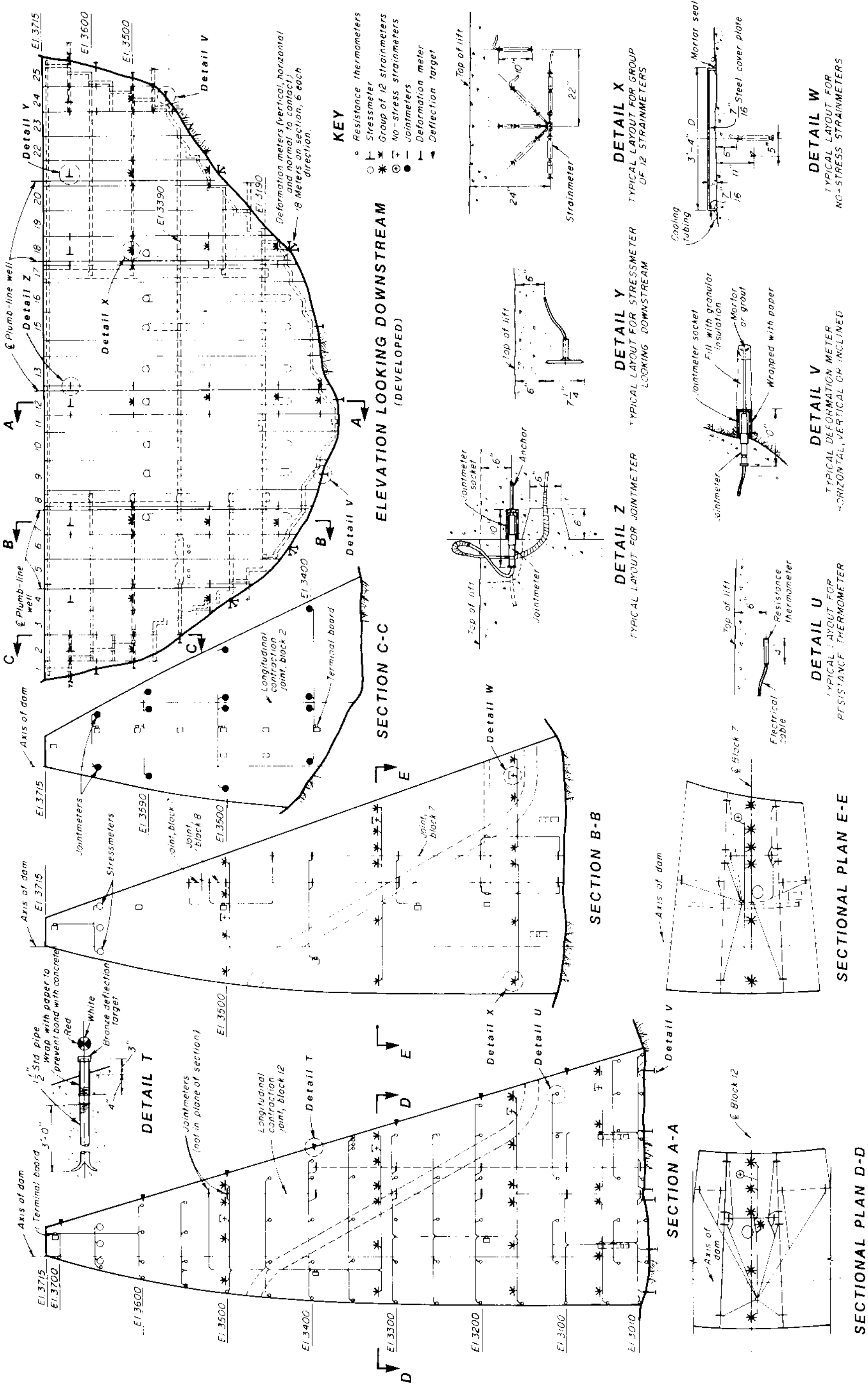
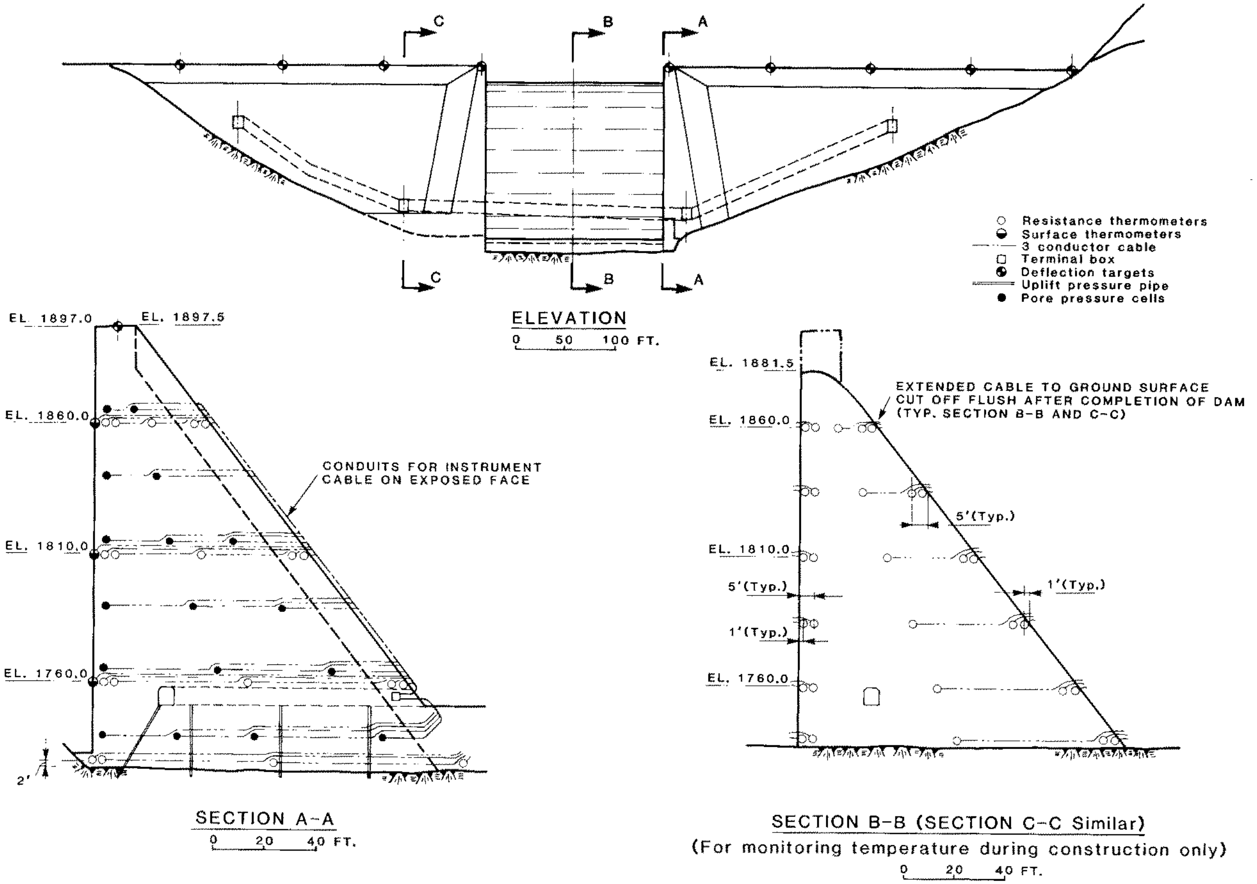


Figure 3-3. Glen Canyon Dam



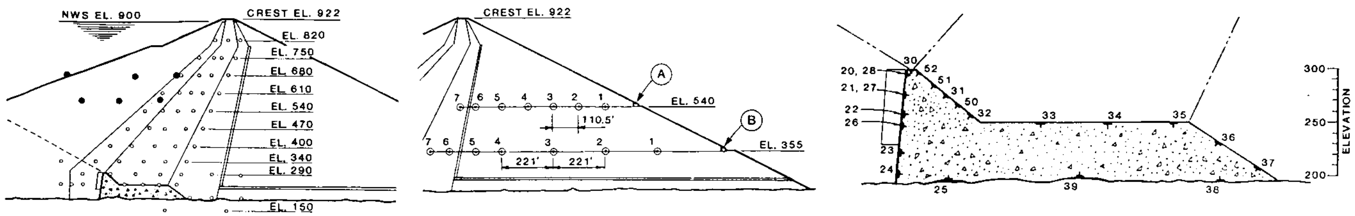
ELEVATION

SECTION A-A

SECTION B-B (SECTION C-C Similar)

(For monitoring temperature during construction only)

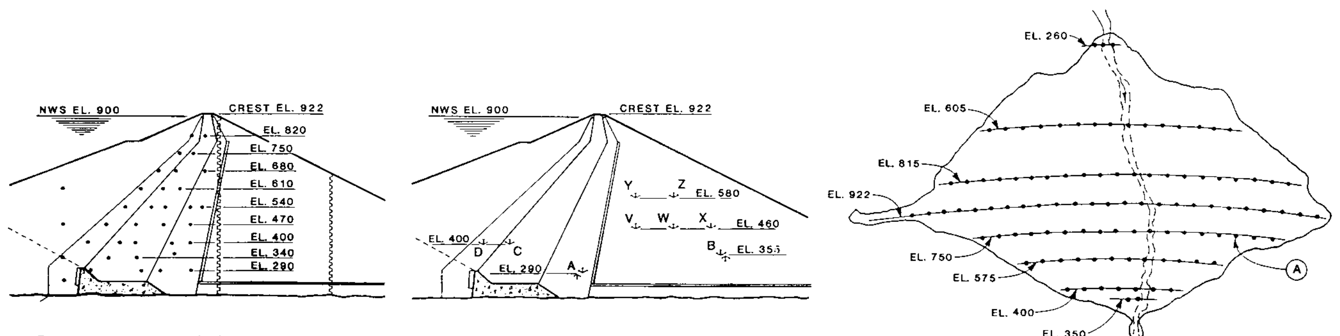
Figure 3-4. Galesville Dam. (Roller Compacted Concrete Structure)



o Hydrostatic measurements
• Hydrodynamic measurements

Ⓐ Instrument house "T"
Ⓑ Instrument house "U"

Location of core block stress meters



• Fluid level settlement device
⌇ Crossarm settlement device

A, B, C, D. Static measurements
V, W, X, Y, Z. Dynamic measurements

Ⓐ Surface reference points

Figure 3-5. Oroville Dam

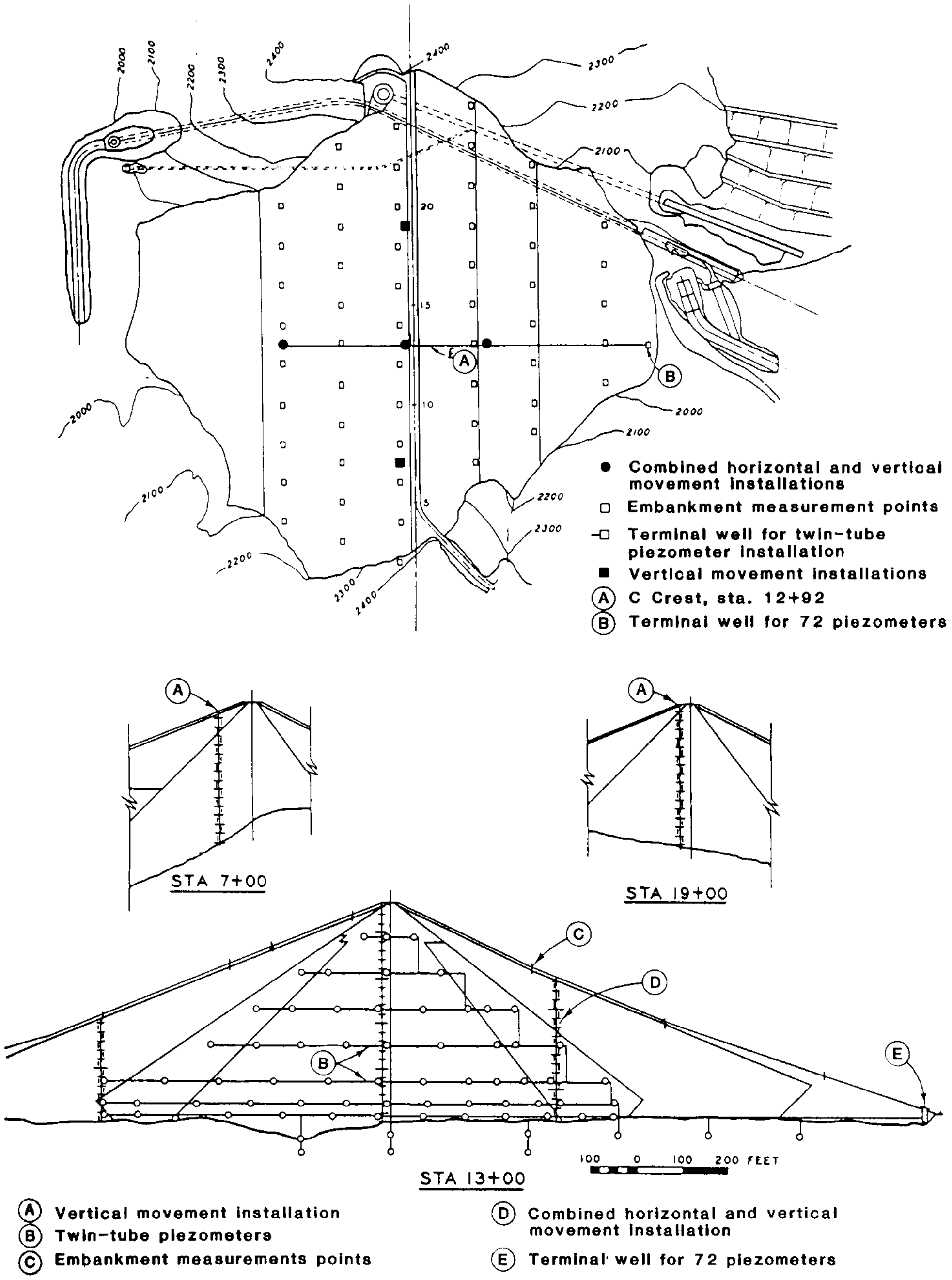
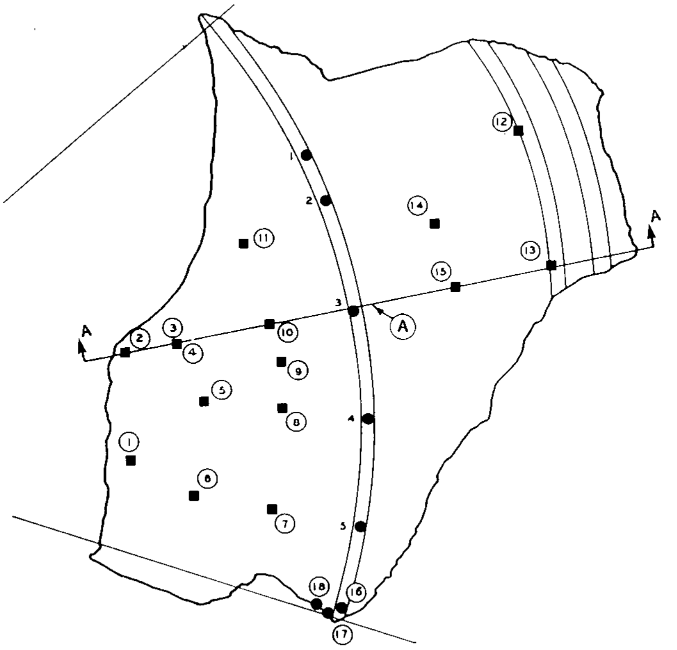
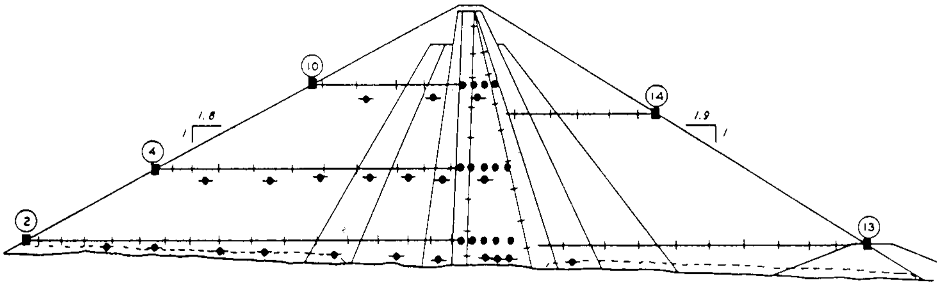


Figure 3-6. Trinity Dam.



● Vertical and inclined settlement tubes
■ Instrument house, exit for horizontal deformation tubes
(A) Section where pressure devices are located



■ Instrument house
-+- Tube with plates
● Pore pressure devices
-◆- Total pressure devices

Figure 3-7. Carter Dam.

TABLE 5-1

INSTRUMENT MONITORING SCHEDULE

PERIOD	TYPE OF MEASUREMENT		
	DEFLECTION/DEFORMATION	STRESS/STRAIN/TEMPERATURE	SEEPAGE/PIEZOMETRIC LEVELS
During Construction	PL - Read weekly. SL - Read prior to filling. FD - Read weekly. MP - Read weekly.	SS - Read weekly. SM - Read weekly. T - Read weekly.	U - Read weekly. D - Read weekly. P - Read weekly.
First Filling	PL - Read daily during fill or each specified rise. SL - Read once after reservoir reaches level to be maintained. FD - Read daily during fill or each specified rise. MP - Read daily during fill or each specified rise.	SS - Read once each specified rise. SM - Read once after reservoir reaches level to be maintained. T - Read once after reservoir reaches level to be maintained.	U - Read following filling. D - Read following filling unless unanticipated flow is encountered. P - Read daily during fill or once each specified rise.
Initial Holding (if applicable)	PL - Read daily for first week, weekly thereafter. SL - Read monthly. FD - Read weekly. MP - Read weekly unless creep is indicated.	SS - Read weekly. SM - Read weekly. T - Read weekly.	U - Read daily for first week, weekly thereafter. D - Read weekly. P - Read daily for first week, weekly thereafter.
Subsequent First Year's Operation	PL - Read bi-monthly. SL - Read quarterly. FD - Read monthly. MP - Read monthly.	SS - Read bi-monthly. SM - Read bi-monthly. T - Read bi-monthly.	U - Read weekly. D - Read weekly. P - Read weekly.
After Dam Attains Stabilized Pattern of Behavior	PL - Read monthly. SL - Once a year at high reservoir. FD - Read monthly. MP - Read monthly.	SS - Read monthly. SM - Read monthly. T - Read monthly.	U - Read weekly. D - Read weekly. P - Read weekly.

PL - Plumblines
SL - Survey Transverse, Triangulation
FD - Foundation Deformation Meters
MP - Multiple Position Extensometers

SS - Stressmeters
SM - Strainmeters
T - Thermometers

U - Uplift Pressure
D - Seepage
P - Piezometers

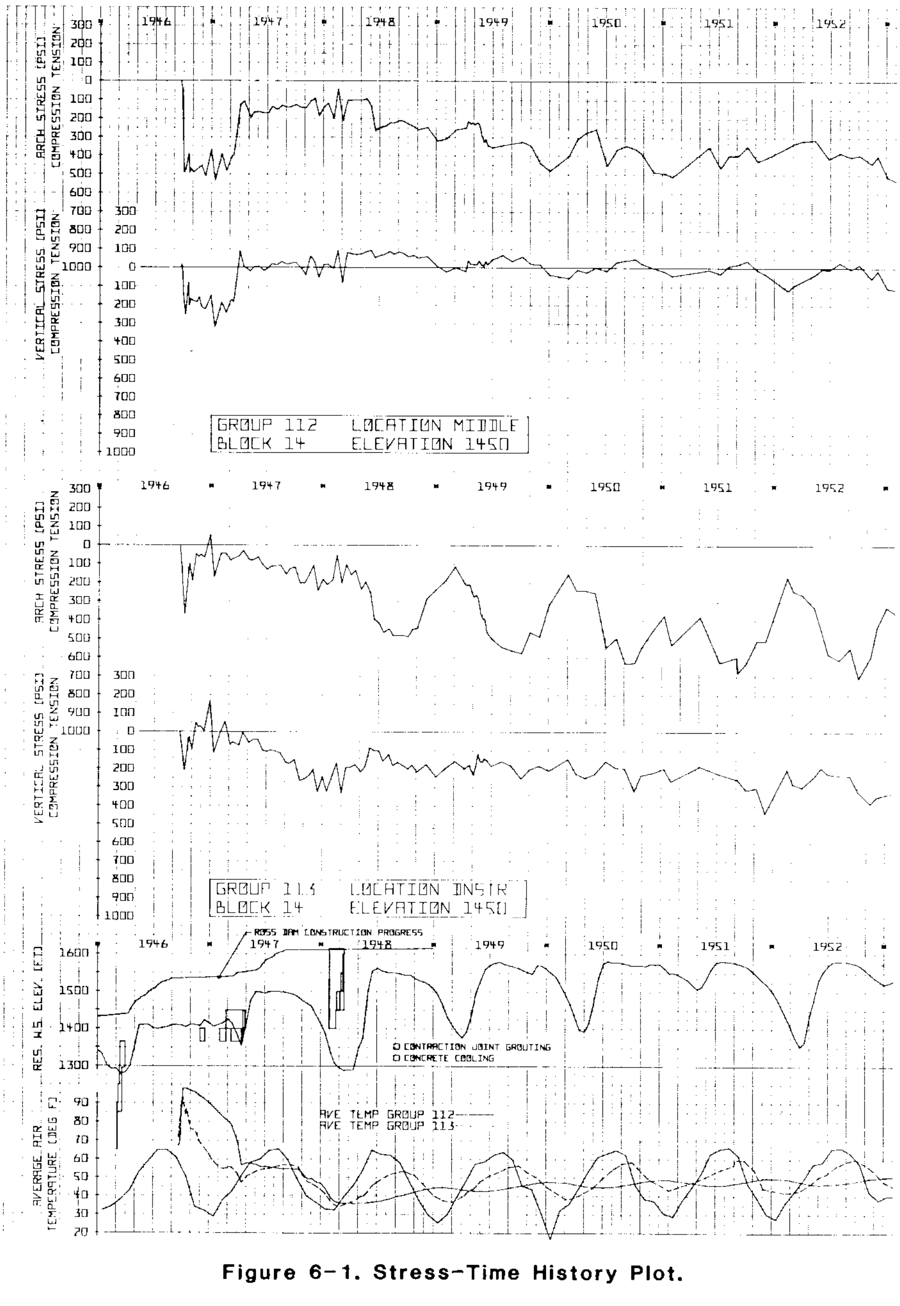


Figure 6-1. Stress-Time History Plot.

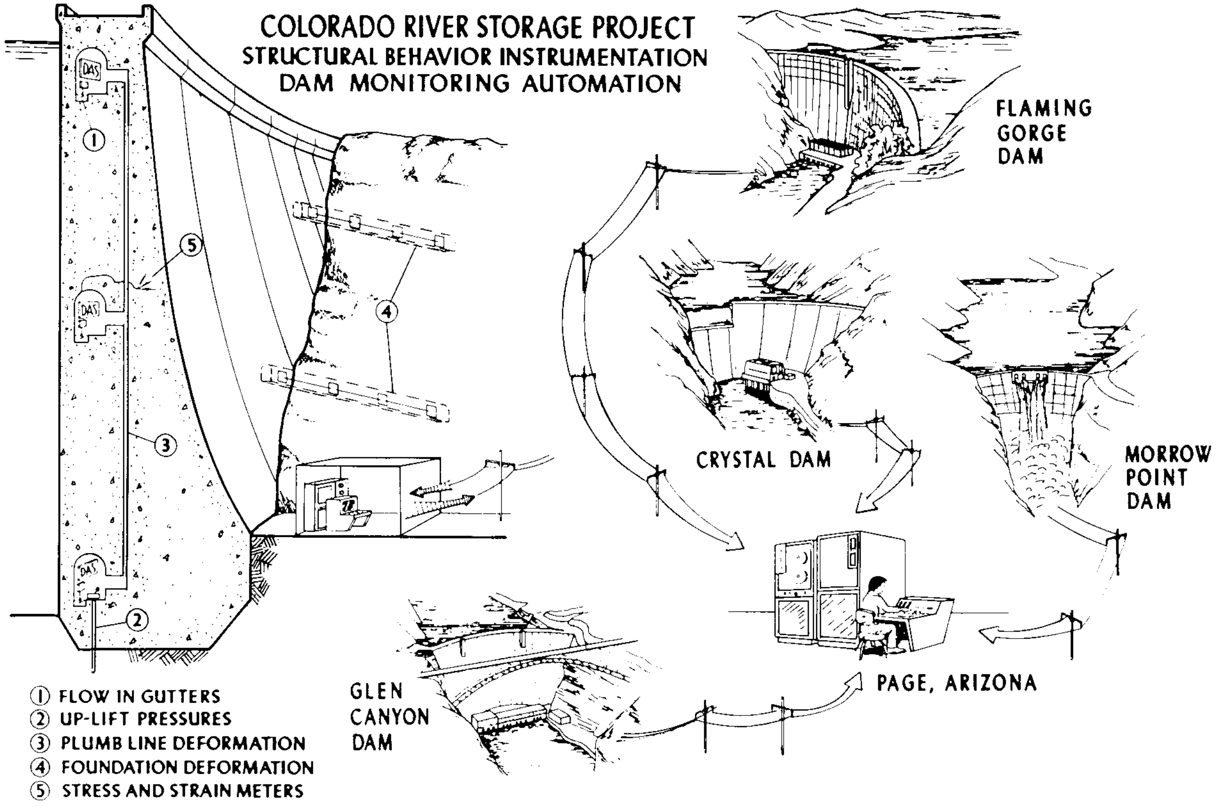

COLORADO RIVER STORAGE PROJECT
STRUCTURAL BEHAVIOR INSTRUMENTATION
DAM MONITORING AUTOMATION
FLAMING GORGE DAM
CRYSTAL DAM
MORROW POINT DAM
GLEN CANYON DAM
PAGE, ARIZONA
DAS
① FLOW IN GUTTERS
② UP-LIFT PRESSURES
③ PLUMB LINE DEFORMATION
④ FOUNDATION DEFORMATION
⑤ STRESS AND STRAIN METERS

Figure A-1.

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