INSPECTION OF DAMS
FOLLOWING EARTHQUAKE GUIDELINES

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Committee on Seismic Aspects of Dam Design (2008)

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FOREWORD AND ACKNOWLEDGEMENTS

Large dams should be able to resist the effects of the strongest ground shaking to be expected at the dam site. However, major damage is accepted as long as there is no catastrophic release of water from the reservoir. Therefore, after a major earthquake – depending on the observed damage - it may be necessary to lower the reservoir or take any other safety measures for the population affected by the failure of a dam. The measures to be taken for different intensities of ground shaking and levels of earthquake damage should be specified in emergency action plans, which are today's state of practice for dams with large damage potential.

Accordingly, the inspection of dams following earthquakes is an important aspect in the integral safety concept of dams. As very few large dams built according to the modern design and safety concepts promoted by ICOLD have actually been subjected to very strong ground shaking or have been damaged in a major earthquake, there exists still very limited knowledge about the performance of dams during such events. As observed in other types of structures, it is well possible that new types of failure may be observed if one of these modern dams will be subjected to very strong ground shaking similar to that expected during the safety evaluation earthquake. The checklists given in this Bulletin will allow (i) a systematic recording of the observed earthquake damage, and (ii) a quick assessment of the safety of the dams and the assessment of the measures to be taken.

The bulletin was first published in 1988. Since then a few earthquakes have occurred, which have also caused damage to dams. We expect that the people in charge of dam safety will have free access to this publication so it can be used effectively for the safety assessment of dams. This has not been the case in the past, therefore, it is also not known if the checklists have been used or not. That there is a demand for such checklists was demonstrated by the 2001 Bhuj earthquake in India, where some 240 dams (mainly small embankment dams) were damaged and needed repair and strengthening. Also during the magnitude 8 Wenchuan earthquake in Sichuan province in China of May 12, 2008, over 1500 dams and reservoirs were damaged to different extent. Moreover, after the magnitude 7.2 Iwate-Miyagi Nairiku earthquake, which occurred in Japan on June 14, 2008, 134 dams were inspected. With the present Bulletin it will be able to make a consistent assessment of the earthquake damage and the safety of dams following strong earthquakes.

We hope that this Bulletin will also be used as the basis for the development of inspection procedures by different organisations responsible for dams.

On behalf of the ICOLD Committee on Seismic Aspects of Dam Design, I acknowledge our debt to USSD for the work involved in the preparation of their document "Guidelines for Inspection of Dams after Earthquakes" which was adopted as the basis for our own Bulletin. USSD updated their Guidelines in 2003 and the changes made have been taken into account in the revision of this ICOLD Bulletin.

I also wish to record special thanks to our Sub-committee members Ian Landon-Jones, Norihisa Matsumoto, and Don Babbit, for steering our discussions on the update of this Bulletin at the Tehran (2005), Barcelona (2006), and St. Petersburg (2007) Committee Meetings.

Martin Wieland
Chairman, Committee on
Seismic Aspects of Dam Design

PREFACE

The original 1988 Guidelines for Inspection of Dams following Earthquakes were prepared by the Committee on Seismic Aspects of Dam Design.

Several existing publications were taken into consideration at the time but it was found that the Guidelines prepared by USCOLD covered almost entirely the subject. It was therefore decided by the Committee to use the USCOLD 1984 publication as the basis of the Guidelines to be issued as an ICOLD Bulletin. Some minor re-arrangements were made in order to reflect more general conditions.

At the 2004 Seoul meeting it was decided that all existing Bulletins that were more than 10 years old should be reviewed and updated as necessary. It was agreed that Bulletin 62 required updating to reflect current trends and as a result of the fact that the USCOLD Guidelines had been recently updated in 2003.

The revised USCOLD "Guidelines for Inspection of Dams after Earthquakes (2003)" were taken into consideration in the update of this ICOLD Bulletin.

Some significant additions have also been made to all parts of the guideline, i.e.:

- Changes have been made to Part 1 further strengthening the need and benefit of Emergency Action Plans as part of earthquake preparedness and planning.
- Mention is now made of the benefit of an assessment of potential failure modes in identifying those areas and features of a dam that could be more susceptible to earthquake damage.
- A new Part 2 and Appendices 2 and 3 have been added describing recent developments in the use of earthquake detection, alarm and response systems in responding to earthquake events.
- Appendix 4 provides new information from Japan on the likely effects of earthquakes on dam leakage and uplift pressures.

It is understood that the Guidelines should serve as a general guide to procedures and that some countries might consider it necessary to introduce further specifications in order to suit more specific requirements.

Inspection immediately after an earthquake is most crucial to the decision regarding continued operation of the structure. A follow-up inspection will provide more detailed information for the design of any repairs and for an insight into structural performance under seismic loading. Inspection requirements for a dam can be made more meaningful by tailoring them for a specific dam using these guidelines.

Additionally it is hoped that the application of these guidelines and publication of the inspection findings will provide dam designers with a wealth of information on dam performance during earthquakes. Dam designers have developed analytical and materials testing techniques which are used to estimate the behaviour of materials and structures subject to seismic loadings. On the basis of these estimates, a design is prepared and the dam constructed. Verification of the adequacy of design and construction methods and the establishment of a high level of confidence in these methods within both the profession and the general public is necessary. Such verification will be greatly enhanced through complete and meaningful reporting on the behaviour of dams and appurtenant structures during earthquakes.

INTRODUCTION

Dams in general have a good performance record in regards to earthquake shaking, with few dams having suffered major damage; Seed (1979), ICOLD (1986), USCOLD (1992), NSWDSC (1993), Hinks & Gosschalk (1993) and Wieland (2003). Where damage has occurred it has been mainly due to liquefaction in embankment dams or their foundations, or damage to appurtenant structures. A few concrete dams have experienced significant cracking. There are very few cases where the degree of damage has led to a dam breach and release of the reservoir. As discussed in ICOLD (1983) less than 1% of dam failures are due to earthquakes. This may have been a fortunate outcome in several of these cases due to low reservoir levels at the time.

Despite the above, earthquakes typically occur with no warning and have the potential to cause dam failures either immediately or due to secondary effects following the earthquake (e.g. aftershocks, piping through new cracks).

In embankment dams (including canal embankments), earthquake impacts include large deformations, settlement and/or cracking. Most cracking is longitudinal, normally found on the dam crest, but traverse cracking has occurred mainly near the abutments.

In concrete dams the major impact is cracking. For example, horizontal or near horizontal cracking has occurred along construction joints at high elevations such as at Koyna gravity dam in India, Sefid Rud buttress dam in Iran and Hsinfengkiang buttress dam in China.

It is therefore important that timely action is taken to inspect dams following significant earthquake events.

In the event of damage, immediate action may be necessary to prevent further weakening of the structure. Accordingly, all dam operators should be carefully instructed in the procedures to be followed if an earthquake should occur that produces motions of intensity sufficient to cause damage.

There are two phases to such an inspection procedure:

- an immediate inspection by the dam operator, and
- follow-up inspection(s) by dam engineering professionals.

Aspects of the inspections are discussed later in the Bulletin, and inspection checklists are given in Appendix 6 to aid in preparing instructions.

1. EARTHQUAKE PREPAREDNESS & PLANNING

Inspections following earthquakes are most meaningful if the procedures are prepared and customized and included in a specific Emergency Action Plan (EAP) for each individual dam. The general procedures described herein may be used as guidelines by professional persons conversant with the design and operation of the dam in the preparation of a set of inspection procedures for a specific dam. The procedures should list all of the features to be inspected, in an order believed to be the most important and efficient. Communication links to designated offices regarding the inspection and findings should be a part of the plan.

Emergency Action Plans (EAPs) should as a minimum be developed for all dams that have the potential to cause major consequences downstream particularly 'loss of life'. Such plans should include:

- Information to advise how quickly a dam may need to be inspected.
- Information that will assist dam operators and emergency responders in determining after an earthquake whether there are any problems, how serious those problems may be or how quickly they may develop.
- Procedures and suggested actions for dealing with the potential or actual post-earthquake emergency conditions including communication to emergency agencies.

An assessment of potential failure modes is a useful way of identifying and prioritizing those areas and features of the dam that could be susceptible to earthquake-induced damage. The results of a thorough analysis of potential failure modes can be applied in:

- Identifying key features of the dam that should be monitored with appropriate instrumentation. Instrumentation data that are collected during normal operation of the dam provide a baseline against which post-earthquake data can be compared.
- Identifying potential seismic deficiencies that should be remediated on a priority basis.
- Identifying features of the dam that could be susceptible to seismic damage or which might provide indication of changed conditions or performance.
- Identifying and documenting contingency plans to cater for the occurrence of such events.

Deployment of an EAP after an earthquake will usually include inspections to assess the condition of the dam. In developing the EAP the dam operator should consider:

- The locations, availability and training of staff who are likely to be the first responders after the earthquake.
- Site access and communication links and the potential for their disruption due to earthquake damage.
- The likelihood of relevant seismic information being available, such as earthquake magnitude, location and intensity of shaking at the dam site.
- The predicted seismic performance of the dam.

- Specific inspection procedures for the dam, listing all of the features to be inspected, in an order believed to be the most important and efficient. The results of a potential failure modes analysis will be valuable in this activity.

If a severe earthquake occurs in some cases dam operators may not be able to get to dam sites by normal means. This may be due to access roads or railway lines being damaged or disrupted due to the earthquake impacts, such as subsidence, landslides or rockfalls. If this is considered possible to occur for a particular dam, then the situation should be properly assessed and appropriate resources be put in place to satisfactorily address the issue. Helicopter access to the site is one appropriate backup measure. However, in some countries, only the military has access to helicopters. Also many helicopters may rapidly get hired by television news crews etc. and there may not be any left for emergency responders; or in certain seasons the rental helicopters may be committed for other purposes, sometimes on long term assignments far from base. In addition severe snow or rain storms may prevent access to helicopters. Therefore preplanning is required to avoid such problems.

If access is prevented for some period of time, more recent sophisticated techniques may now be available to be used to undertake an initial assessment to detect any significant damage such as: aerial laser scanning, Google Earth (internet) etc although there may be delays in this information becoming available.

Telephone and other communication systems are prone to suffer damage and/or interruption following earthquake events. It is therefore preferable that more reliable systems that are customised for disaster emergency situations be established at the dam site, e.g. satellite phones.

Power failure often happens due to an earthquake, so standby power is indispensable in being able to operate equipment related to the safety of the dam.

It is very important that dam operators have undergone relevant training and have the necessary experience to be able to properly assess a dam and determine the potential for an emergency situation at a dam during the critical first inspection.

Emergency Action Plans should be regularly reviewed, tested and exercised such that all involved parties become familiar with the dam and trained in the responses that may be required and so that the plan remains relevant and appropriate for current conditions.

It is also very important that relevant reference materials such as drawings, design and construction documents and other data on all aspects of the dam are readily available at the dam site for immediate referral in the event of an emergency or incident at the dam.

2. EARTHQUAKE DETECTION AND ALARMS

An emergency response to an earthquake should consist of three separate steps or processes, namely:

- Collection of seismic data.
- Processing of the data and issuing suitable warnings or alarms.
- Response to warnings (e.g., dam inspections).

The lack of any of the above three processes has the potential to reduce the effectiveness of the overall response. Dam operators or emergency response staff benefit from prompt intelligence that allow them to deploy their Emergency Action Plans (EAPs) effectively.

This section of the Bulletin provides information on the first two processes.

2.1 SEISMIC DATA COLLECTION

The establishment of seismometer and strong motion accelerometer networks around dams has become more common in recent times. These may be established and operated by individual dam owners but more commonly by national agencies. Ground motion data collected at individual sites within the network can be transmitted to a central location via various means, including:

- Continuous transmission via satellite (VSAT) or landline.
- Dial-up or continuous real time internet telemetry.
- Event-triggered telemetry via mobile (cell or satellite) phones or radio links.

Data collection systems are more reliable if they have some form of redundancy built into them. The telemetry links should use different modes of communication; however, satellite communications should generally be immune to disturbance from earthquake events provided they are equipped with reliable uninterruptible power supplies.

Back-up power supplies such as batteries and solar panels should be provided otherwise there is a risk that power may not be available when an earthquake occurs. The provision of some redundant instruments in a network can also be considered.

Damage to seismic instruments can and has occurred as a result of an earthquake. Therefore instrument installations should be able to withstand the largest ground motion expected to be experienced. Instrument recorders should have sufficient memory capacity and data should be downloaded promptly otherwise the recording of aftershocks may overwrite the major earthquake data.

The next step involves the interpretation of the data. This can be done by manual processes but with modern technology “intelligent” software systems can automatically interpret the recorded ground motion received from various sites and automatically estimate the intensities felt at the specific dam sites and in the surrounding area. This interpretation can produce useful outputs consisting of plots (e.g. shake maps), reports and recommendations.

2.2 EARTHQUAKE WARNINGS AND RECOMMENDATIONS

The next process is to provide as much useful and easy to understand information to dam operators to allow inspections and other emergency responses to be coordinated.

A significant earthquake could impact on multiple dams under the jurisdiction of the dam owner. For example following the January 26, 2001 Bhuj earthquake in Gujarat, India some 240 dams (mainly small embankment dams) needed repair and rehabilitation. With the possibility of limited resources to implement immediate dam inspections and the current trend in some countries or agencies of dams not being manned on a 24-hour basis, there is strong justification for advice or warnings being given on a priority basis.

General advice can be provided in the EAP on the times within which initial inspections should be carried out but circumstances in some cases at specific dams may prevent such times to be achieved. It may not be possible to get road access to some remote dams for several days or weeks due to disruption of transportation links, or for other reasons as noted in Section 1. It may be possible to install sensors or remote cameras at such dams (with appropriate reliable power supplies) to assist in detecting problems at dams.

Such advice can be provided in many ways. Examples of current practices in several countries are provided in Appendix 2. However, in many cases such systems are not in place or it may be very difficult for operators and responders to get information in a rapid manner. It is therefore best to have a simple plan, at least as a backup, that does not rely on specific information being provided before an inspection is carried out. For example, dam operators should be instructed and trained such that in the event that they feel an earthquake or hear news reports of an earthquake in the vicinity of a dam, but have received no more specific information about the magnitude or shaking levels etc., they are to carry out an immediate dam inspection without waiting to receive further information or instructions.

3. IMMEDIATE INSPECTION FOLLOWING EARTHQUAKE

The effectiveness of emergency response actions depends on prompt detection and evaluation of any unusual condition. It is therefore important that suitably qualified and trained personnel undertake the inspections. In addition, the need for timely action in the event of an emergency cannot be over-emphasised.

Where several or a large number of dams could have experienced the impacts of an earthquake the priority upon which inspections should be undertaken should take account of the following factors: peak ground acceleration or level of intensity at the dam site, the susceptibility of the dams to earthquake shaking and the consequences of failure of the dams.

If a response system, as described in Part 2, is not available, then it is suggested that the dam operator be given instructions according to the following guidelines for inspection of the facility immediately following an earthquake. If no operator is posted at the dam site, representatives of the organization responsible for the dam should undertake the inspection, following the same guidelines.

3.1 WHEN COMMUNICATION LINKS ARE IN PLACE

If an earthquake is observed at or near a dam, or one has been reported to have occurred, with a Richter magnitude greater than and within a radial distance as set out in the table below, follow these procedures:

Magnitude	Distance (km)
>4.0	25
>5.0	50
>6.0	80
>7.0	125
>8.0	200

Note: these combinations have been chosen such that a significant intensity level is expected to have been experienced at the dam site. An alternative trigger for inspection could for example be an intensity of shaking of greater than MMI 4 experienced at a dam site.

a) Immediately conduct a general overall visual inspection of the dam and major appurtenant structures.

b) If the dam is damaged to the extent that there is increased or new flow passing downstream, or there are other signs indicating a potentially imminent failure, then immediately implement the specific failure or impending failure procedures as set out in the Emergency Action Plan for the dam.

c) If abnormally reduced flow is present at the upstream end of the storage, immediately inspect the river course for possibility of upstream damming due to landslide. If such is the case, implement failure or impending failure procedures.

d) If visible damage has occurred but has not, or in the best judgment of the inspector, has clearly not been serious enough to cause failure of the dam in the near term, conduct a more detailed inspection and make the following observations and contacts immediately:

   1) Observe the nature, location, and extent of damage and the rate of any changing conditions. The description of damage such as slides, sloughs, and previously undetected subsidences should include location, extent, rate of subsidence, and effects on adjoining structures (or cracking, offsets or leaks in concrete structures). Observations of other facts believed to be pertinent, such as springs or seeps, reservoir and tailwater elevations, and prevailing weather conditions should also be made. Evaluate potential for failure. Make an estimate of the intensity of the earthquake using the Modified Mercalli Intensity Scale shown in Appendix 1, or such Intensity Scale which is used in the country.

   2) Report all information to the *(Supervisory)* Office, or, if key personnel are not available, report directly to the Headquarters Office. If communications cannot be established with these personnel, report directly to any responsible agency. When making a phone or radio report, be absolutely sure to state the dam name, your name, extent of damage and nature of any response or action required. When damage exists, it is extremely important that the one receiving your report understands your evaluation and description of the potential hazard at the dam. A decision on further actions required must be promptly made in accordance with the EAP.

   3) Reinspect the site of the damage and maintain communications with the key personnel previously receiving the report. Take photographs or video and record or make notes on observations. Using a digital camera will allow photographs to be immediately sent to others.

   4) Be prepared to make additional inspections at any time because of possible aftershocks.

   5) If there is definitely no impending dam failure, continue to step (e).

e) Thoroughly inspect the following for damage such as using a customized checklist for the specific dam: (this checklist would ideally have been developed based on a failure modes analysis if one had been previously performed).

   1) The crest and both faces of the dam for cracks, settlement, displacement, or seepage.

   2) Abutments for possible displacement, cracks, new springs, or large rocks that may have been or are being displaced.

   3) Drains and seeps for increased flow or stoppage of flow.

   4) Spillway structures and gates for misalignment or structural distress.

   5) Outlet works control house, tunnel, and gate chamber for cracks or spalling of concrete, displacement, or valve or gate misalignment.

6) Powerplant facilities for cracks, spalling, tripped-out generators, gate or valve distress, and for any indication of water passage failure.

7) Power supply and standby power unit, and other emergency operating equipment.

8) Visible reservoir and downstream areas for landslides, new springs and sandboils, and rockfalls around the reservoir and in downstream areas.

9) Canal headworks for cracks, spalling, or structural distress.

10) Other appurtenant structures for signs of distress.

11) Tunnels and conduits, for silt, sand, gravel, rock, or concrete fragments being carried in the discharge stream.

f) Undertake whatever actions or notifications that are required under any specific EAP for the dam, but specifically report findings to the *(Supervisory)* Office or to other personnel in the Headquarters Office to whom you previously reported after the earthquake.

g) If no apparent damage has occurred to the dam, embankment, or appurtenant structures, a “No Damage” report must be made to the *(Supervisory)* Office.

h) Continue to inspect and monitor the facilities for at least 48 hours or as instructed by the *(Supervisory)* Office because initially unobservable or delayed damage may subsequently become apparent or occur.

i) The full nature and extent of damage or even the presence of damage may not be readily apparent during an inspection immediately following an earthquake. It is possible that settlement of structures, reactivation of old slides, or development of new slides or springs may not occur during ground shaking but could appear after the initial inspection. A secondary inspection 2 weeks to a month after the initial inspection should be made.

j) Information on the condition of the structures and their performance with respect to the earthquake may be obtained from readings on the instrumentation installed in the dam and foundation including pendulums, inclinometers, extensometers, survey monuments, piezometers, and seismographs installed in the dam and foundation.

Data should be collected from all instrumentation as described in the instructions and schedule for reading instruments. A schedule of very frequent readings should be followed for at least 48 hours after the earthquake.

It is important for the *(Supervisory)* Office to contact the appropriate seismological organization to obtain all available information and to determine whether aftershocks may be likely. Such information will guide further activities at the dam.

A report on the inspections after an earthquake should be prepared particularly if damage has occurred or unusual events have been noticed (e.g. increased leakage or uplift pressure) in order to document specific details of what has occurred.

Access to a boat may be useful to enable inspections of upstream foreshores. Taking photos from an airplane after an event is recommended to record details of damage if it has occurred.

It is also important to have documented evidence of any pre-existing cracking of concrete dams and cracking and/or settlements of embankment dams to enable easy identification of any changes following an earthquake.

3.2 WHEN COMMUNICATION LINKS ARE NOT AVAILABLE

a) If all communications from the dam are lost and there has been significant shaking experienced and/or there is a potential danger for failure of the dam, use the following checklist as a guide:

1) Quickly inspect the dam and abutments for sloughs, slides, slumps, springs or seeps, and other signs of distress near dam abutments.

2) Evaluate potential danger of failure, to the best of your ability.

3) If failure is or is judged to be imminent, warning to downstream residents is essential. The responsibility for such warning varies between different countries, dam owners, states etc. Therefore the responsibilities should be clearly defined, normally within the specific EAP for the dam.

4) If failure is imminent, all measures should be used to reduce storage in the reservoir. Caution should be used in increasing discharge through the outlet works because the conduit may be sheared and increased flow could cause erosion of the structure or piping of the dam embankment. It may be necessary to cut off the flow in the outlet works (if possible) to avoid piping or other severe damage.

5) Continue to attempt to establish or maintain contact with any *(Supervisory)* Office.

4. FOLLOWUP ENGINEERING INSPECTION

In the event that the dam operator reports that damage has occurred or there is the potential for damage due to severe shaking, qualified engineering personnel should be dispatched as rapidly as possible to the dam to make a technical evaluation of the extent of damage and the degree of hazard it presents. The members of such an inspection team should be familiar with the possible modes and causes of failure of a dam and its associated structures, and should also be familiar with the main features of the project. Suggested checklists for use in this phase of the inspection are presented in Appendix 6, and guidance for the inspection is given in this Section.

4.1 POSSIBLE MODES AND CAUSES OF FAILURE

The members of an inspection team must be aware of the modes of dam failures. Research and study of previous failures are required for the team members to reinforce their engineering understanding of how and why failures occur. Of particular value are the Publications on Dam Incidents and Dam Safety (ICOLD Bulletin 46).

Weaknesses in a dam or foundation may take many forms. Some of the more common causes of dam failures, and examples of adverse conditions are discussed in this Section. Adverse conditions that can lead to failure are categorized:

Failure Category	**Causes**
Abutment and foundation instability	• Liquefaction • Slides • Subsidence • Removal of solid and/or soluble materials by water • Settlement • Joint openings and/or grout curtain rupture • Movement on faults under or adjacent to dam • Change of water level (e.g. due to fracture of grout curtain or upstream subsidence)
Defective spillways	• Obstructions • Broken linings • Damaged gates and hoists • Slab displacement

Defective outlets	• Obstructions • Damaged gates and hoists • Displaced or damaged linings
Concrete dam defects	• Blocked drainage or high uplift • Unanticipated uplift distribution • Differential displacements and deflections • Excessive seepage • Overstressing, as may be evidenced by cracking or crushing of the concrete
Embankment dam defects	• Liquefaction, sand boils • Slope instability • Excessive seepage • Removal of solid and soluble materials • Soil erosion • Embankment settlement leading to inadequate freeboard • Cracks or sinkholes opened by seismic activity • Longitudinal or transverse cracking • Cracks in upstream concrete face slabs • Damage to waterproofing systems in upstream face
Reservoir margin defects	• Slope instability • Inherent weaknesses or natural barriers • Sinkholes opened by seismic shocks • Landslide blockage of upstream watercourses • Landslide causing seiche and/or increase in reservoir water level

4.1.1 Abutment and Foundation Deficiencies

These deficiencies are associated with the quality of the abutment and foundation materials or with their treatment. Differential settlements, slides, excessive water pressures, weak seams or zones, and inadequate control of seepage are all common potential failure mechanisms within an abutment or foundation.

Abutments and foundations which have a low shear strength or seams of weak material such as shales, bentonite, or fault gouge can result in sliding of the foundation and embankment. Also, seams of pervious material in the foundation, which have no provisions for pressure relief, can form excessive uplift pressures and cause sliding.

Seepage through abutments and foundations can cause piping of solid materials or the erosion of soluble materials by solutioning. This removal of material forms voids, which can increase until a portion of the remaining unsupported material collapses and failure of a section of the abutment or foundation occurs. Water can also cause a breakdown of some foundation materials such as shales, or reduce the shear strength of the foundation rock or the dam-rock contact.

The reduced stability of an abutment, weakened by the effects of an earthquake or other means, can have a significant effect on the overall stability of an arch dam.

Some of these weaknesses can be identified by visual examination of the foundation environs during a site inspection. Visible cracks in a dam can be indicative of foundation movement. Visual evidence of piping would be sediment in the seepage water (turbidity), whereas the washing of soluble material into solution would require chemical analyses to detect solutioning.

4.1.2 Spillway and Outlet Works

Many adverse conditions such as obstructions to the flow, structural weaknesses, or faulty underdrains can be identified by visual examination during a site inspection. Structural failure in a conduit, tunnel or other conveyance structure or a significant rockfall into a spillway for example could obstruct the flow in the system, which would be evidenced by a reduction or unusual turbulence in the flow. Loss of the power source to operate facilities may also present operational conditions which compromise the safety of the dam.

Spillways and outlet works controlled by gates and/or valves can only function as designed if the gates and valves can be operated as intended. If a spillway or outlet works cannot be operated due to faulty gates, valves, or operating equipment, the dam could be in danger of failure. Faulty operation of gates, valves, or operating equipment can result from settlement or shifting of the support structure, and could cause binding of gates or blockage by debris. If damage is suspected or likely, gates should be operated soon after the earthquake to verify operation.

Slides from the slopes above the inlet can block the approach channel. Slides could also damage the intake structure and associated metalwork such as gates, hoists, and motors.

Cracking and movement of concrete structures may indicate distress. Floor slabs in a chute and stilling basin may be displaced by seismic activity, and may change the drain capabilities and cause excessive uplift.

Concrete dam crest structures (such as gate house for emergency closure valves) should be inspected because they would be subjected to amplified shaking. This shaking can commonly be 5 to 10 times that of the foundation and dam crest structures are not normally designed for such.

4.1.3 Seepage

The main source of seepage within a concrete dam is through contraction joints or along unbonded construction joints or lift lines. Cracks in the mass concrete are also a potential source of seepage in the structure. Formed drains installed in the dam are designed to intercept the seepage and reduce the pressures which could develop along lift lines.

Uncontrolled seepage through an embankment dam or foundation can cause the movement of soil to unfiltered exits, creating voids which can lead to a “piping” failure, and result in excess pore pressures, which weakens the soil mass and may cause springs, boils, or slope failures.

Uncontrolled seepage through the abutment or foundation of a concrete dam can form “pipes” or voids, causing bridging of sections of the abutment and resulting in an undesirable concentration of stresses in the concrete. In the abutment or foundation of an earth dam, uncontrolled seepage also can form “pipes” or “tunnels” under the embankment, which can cause the collapse of surrounding materials. This can then lead to the formation of settlement cracks or ultimately to breaching of the embankment. Seepage and piping damage may not be evident for some days or weeks after the earthquake so continued inspection is important.

Increased uplift at the base of the dam from percolation or seepage of water along underlying foundation seams or joint systems may be an indication of reduced effectiveness of the foundation grouting and the drainage system. If the uplift values are extreme or exceed the design assumptions, dam instability may occur.

4.1.4 Defective or Inferior Materials

Low-density, saturated, cohesionless soils in an embankment or abutment or foundation can experience an increase in pore pressure and loss in shear strength when subjected to earthquake-induced shear stresses.

Depending on a variety of factors including material properties and in place conditions, pre-earthquake stress conditions, and magnitude and duration of seismic-induced stresses, the embankment or its foundation may exhibit instability, excessive vertical settlements, and loss in freeboard, or cracking. Embankment dams constructed by hydraulic fill techniques have been found to be particularly susceptible to earthquake-induced damage because of the potential for liquefaction under earthquake loading.

Weak concrete, due to poor aggregate, inadequate lift joint preparation, deterioration with age for example, is vulnerable to damage.

4.1.5 Concrete Dam Overstressing

Overstressing in a concrete dam normally creates areas of distress and cracking that usually can be identified visually. Cracking, opening of lift lines or construction joints, changes in seepage, and differential movements are all indications of potential overstressing. The overstressing may occur along the foundation because of differential or extreme foundation movements, or at any location in the mass concrete of the dam where stresses are excessive. The overstressing may be due to unusual external loading conditions such as earthquakes, temperature variations, contraction joint grouting pressures, foundation movements, or excessive uplift pressures in the foundation or along unbonded lift lines.

4.1.6 Reservoir Margin Defects

Landslides are the most prevalent form of instability affecting reservoir margins. The size of a landslide usually is the primary consideration when evaluating safety aspects; however, a small landslide in a critical location could disable a spillway or outlet and create an unsafe condition for the dam.

Landslides may dam watercourses into reservoirs. Subsequent overtopping of the landslide dams can cause them to fail rapidly and send surges to reservoirs threatening the dams impounding them and their appurtenant structures.

Landslides into the reservoir can cause flood waves (seiches) and dam overtopping (e.g. Vaiont Dam).

Faulting that exists within the vicinity of a dam site and the reservoir has the potential for reservoir-triggered seismic events for reservoirs that are large in size.

4.2 FEATURES TO BE INSPECTED AFTER EARTHQUAKE

All features should be inspected to determine whether there are any changes that may have been a result of the earthquake. Notes should be taken or observations recorded. Sketches, photographs or videos may help to describe the nature and extent of any damages. Photographs should be obtained as soon as possible of any visible results from the seismic activity. These records will be invaluable in determining if there is additional distress developing in the structures. Photographing with a digital camera and locating observations and photographs using a geographic positioning sensor, if available, allows the information to be immediately transmitted and readily incorporated into incident reports. Measurements and readings should be taken of all instrumentation installed in the dam and foundation and in the immediate area. Additional precise surveys, temporary strong-motion seismographs, and other instrumentation may be desirable to monitor structures and individual damage locations. Special steps need to be taken to ensure that records from the seismographs are properly extracted and given to those responsible for their interpretation.

4.2.1 Embankment Dams

The external surfaces of an embankment dam can often provide clues to the behaviour of the interior of the structure. Liquefaction is a special problem for susceptible embankment dams and foundations as a result of earthquake shaking. For this reason, a thorough examination of all exposed surfaces of the dam should be made.

The embankment should be carefully examined for any evidence of displacement, cracks, sinkholes, springs, sand boils and wet spots. Any of these conditions may be in a developing mode and, if they worsen and are not corrected, ultimately could lead to failure of the embankment.

Surface displacement on an embankment often can be detected by visual examination. Sighting along the line of embankment roads, parapet walls, utility lines, guardrails, longitudinal conduits, or other lineaments parallel or concentric to the embankment axis can sometimes identify surface movements of the embankment. The crest should be examined for depressions and crack patterns that could indicate sliding, settlement, or bulging movements. The upstream and downstream slopes and areas downstream of the embankment should be examined for any sign of bulging, depressions, or other variance from smooth, uniform face planes. If a permanent system of monuments for measurement of movement exists, and if any movement is suspected, a resurvey should be made without delay.

Cracks on the surface of an embankment can be indicative of potentially unsafe conditions. Surface cracks are often caused by desiccation and shrinkage of materials near the surface of the embankment; however, the depth and orientation of the cracks should be determined for a better understanding of their cause. The depth and extent of cracks can be observed by first filling the cracks with dye and then excavating. Otherwise it can be difficult to identify the extent of cracking. Openings or escarpments on the embankment crest or slopes can identify slides and a close examination of these areas should be made to outline the location and extent of the slide mass. Surface cracks near the embankment-abutment contacts, and contacts with other structures can be an indication of settlement of the embankment and, if severe enough, a path for seepage can develop along the contact. Therefore, these locations must be thoroughly examined. Cracks can also indicate differential settlement between embankment zones. Trenches are often excavated by machine or by hand to determine the depth of cracking.

The downstream face and toe of the dam, as well as areas downstream of the embankment, and natural abutments should be examined for wet spots, boils, depressions, sinkholes, or springs, which may indicate concentrated or excessive seepage through the dam or abutments. Any of these conditions may be in a developing mode and, if they worsen and are not corrected, ultimately could lead to failure of the embankment. Other indicators of seepage are soft spots, deposits from evaporation of water, abnormal growth or vegetation and, in colder climates, ice accumulation or areas where rapid snowmelt occurs. Seepage water should be examined for any suspended solids (turbidity) and, if solutioning is suspected, samples of the seepage and reservoir water should be collected for chemical analyses. Seepage also should be tested for taste and temperature to help identify its source. If saturated areas are located, they should be studied to determine if the wet spot(s) are a result of surface moisture, embankment seepage, or other sources. Wet areas, springs, and boils should be located accurately and mapped for comparison with future inspections. Seepage should be measured and monitored on an increased frequency to ensure that an adverse trend does not develop which could lead to an unsafe condition.

Drainage systems should be inspected for increased or decreased flow and for any obstructions which could plug the drains.

In addition to verifying anticipated embankment and foundation performance, instrumentation also can be an indicator of developing unsafe conditions. Readings should be made frequently, if earthquake shaking has changed the historical steady state readings. Earthquakes can cause increases in pore piezometric levels by shaking-caused soil volume reduction and/or shearing, and indirectly by earthquake compacted soils transferring loads to stiffer soils.

4.2.2 Concrete and Masonry Dams

Concrete dams encompass a variety of structures which include gravity, slab and buttress, multiple arch, and single arch dams. Masonry dams may be considered as gravity structures with many joints. Regardless of the type, all dams are subject to the same basic considerations with respect to safety.

The dam should be checked for indications of excessive stress and strain as well as signs of instability. Most dams have survey points and/or plumblines for regularly scheduled measurements of movement within the dam, the results of which can be plotted to determine the behavioural trend. There are obvious indications of movement which can be noted during an inspection. A gravity or masonry dam usually can be checked by sighting along the parapets or handrails from one abutment to the other. Each contraction joint or row of masonry blocks should be examined for evidence of differential movement between adjacent blocks. The joints should be examined for evidence of excessive expansion or contraction and excessive movement. The foundation contacts should be examined for any evidence of differential movement between the dam and the foundation.

All cracks and spalls on the dam faces and in the galleries should be examined. Gravity dams would more likely show new cracking in the upper part of the dam, and arch dams near the abutment and top arch. Gallery cracks should be examined to see if they coincide with face cracks. Cracks and spalls noted during past inspections should be examined for any change of condition. New cracks and spalls should be noted and examined to determine the type, such as tension or crushing and the reasons for their existence. They should be marked and measured so that any changes can be detected during subsequent inspections.

Seepage should be examined to determine the possible sources such as poor bond on lift lines, waterstop failure, structural cracks, and erosion of mortar. The quantity of seepage should be compared with previously observed quantities to determine if there has been any significant change in the flow for similar reservoir elevations.

Drain and weep holes should be checked to determine if they are open and functioning as designed. Drains in the foundation and the dam should be examined to determine if there have been significant changes in their flow.

4.2.3 Abutments and Foundation

Critical areas of the abutments and foundations are usually covered and not available for direct inspection. Inspection of upstream portions of the abutments and foundation is normally not possible because of reservoir storage. Therefore, physical examination is typically limited to the downstream abutment contacts, toe of the dam and foundations of some appurtenant structures. Grouting and drainage tunnels also may be available for inspection. Reaction of structures often reflects foundation changes.

Indications of harmful seepage may be quite obvious or very subtle. Changes in measured flow from monitored drains, whether increases or decreases, are immediately suspect. Another indication of changes might be increased frequency of sump pump operation. The presence of suspended particles in seepage water is evidence that piping is taking place and is cause for immediate concern. Joint opening caused by earthquake shaking can rupture grout curtains. On the other hand, small increases in seepage (less than one litre/second - but this would depend on the individual size and nature of dam) are common and are apparently caused by minor opening of rock joints or dislodging or movement of fines in fractures.

Temporary changes (both increases and decreases) in seepage and piezometric pressures are common and should normally start to return to pre-earthquake levels within a few hours after the earthquake however in some cases they may be permanent or take a long time to reverse. Refer to Appendix 4 for case histories of impact of earthquakes on leakage and uplift pressures in Japan.

When the possibility of solutioning exists, samples of reservoir and seepage water should be collected for water quality analyses. Such analyses can identify the soluble material. If the rate of seepage can be determined, the rate of solutioning can be estimated.

4.2.4 Reservoir

The reservoir basin usually does not directly affect the stability of the dam; however, the reservoir should be examined for features which may compromise the safe operation of the dam and reservoir. Immediately upstream of the dam and its abutments the reservoir surface should be inspected for indications of abnormal flow patterns that may indicate gross leakage is taking place. These may include whirlpools or an unusual flow pattern.

The region around the reservoir should be examined for indications of problems which might affect the safety of the dam or reservoir. Landforms and regional geologic structures should be assessed. Areas of mineral, coal, gas, oil, and groundwater extractions should be examined. The region should be checked for subsidence indications such as sinkholes, trenches, and settlement of highways and structures. The reaction of other structures on the same formation may provide information on the possible behaviour of the dam and appurtenances. Whenever an inspection is made, the elevation of the reservoir should be recorded.

The reservoir basin surfaces should be examined for depressions, sinkholes, or erosion of natural surfaces or reservoir linings. The reservoir basin should also be inspected for excessive siltation, which can adversely affect the loading of the dam or obstruct the inlet channels to the spillway or outlet works.

The drainage basins in areas adjacent to but on the outside of the reservoir rim should be examined. Any new springs or seepage areas may indicate that reservoir water is passing through the reservoir rim. Such seepage also may cause land instability in these areas.

4.2.5 Landslides

Landslides, as used herein, include all forms of mass movement that can affect the dam, appurtenances, reservoir, or access routes. They include active, inactive, and potential slide areas which can range from minor slope ravelling to large volume movements. In addition to slide phenomenon, the inspection also should determine if there has been any toppling or sliding of intact rock blocks or masses. These can occur not only in the reservoir but also in the abutments of the dam and above powerhouses. Landslides might form natural dams on tributary streams or cause waves on reservoir surfaces.

At least one team member should be knowledgeable about landslide causes, mechanisms, characteristics, symptoms, and treatment. Slide areas often can be identified by escarpments, leaning trees, hillside distortions, or misalignment of linear features.

4.2.6 Appurtenant Structures

All appurtenant structures that could affect the safe operation of the dam should be examined. These structures include the spillway, outlet works, power outlets and powerplants, and canal outlets. Inspection of critical components such as spillway gates or bottom outlets may not be adequate to verify their operability and in these cases these components should be physically tested and exercised. Each of the structures may be composed of any or all of the following features:

Inlet and Outlet Channels

Practically every hydraulic structure is served by inlet and outlet channels composed of cut or fill slopes of soil or rock. Most soil- or rock-lined spillways have a concrete or solid rock control section to reduce seepage or erosion potential past the dam. Outlet works inlet channels are usually submerged and may require special underwater investigation. Channel protection adjacent to the energy dissipation structure should be examined to determine if it is performing as designed. Special attention should be given to the possibility that the material may wash either out of the channel or back into the structure during operation.

The channels should have stable slopes and be free of sloughs, slides and debris, and should be examined for evidence of sinkholes, boils, or piping. The channels should provide satisfactory clearance around intake and terminal structures so the structures can operate hydraulically as designed.

The outflow water should be examined for the presence of rock and soil or concrete fragments, which may mean that the conduit has been breached and embankment or foundation material is being eroded. On the other hand, the source of turbidity may only be reservoir sediments that were stirred up by earthquake shaking. Repeated observations are usually necessary to identify the source of turbidity.

Dam Safety Critical Plant

Dam safety critical plant, such as gates and valves required by dams to provide flood protection and to reduce loads on the dam after the earthquake shaking should be inspected for operability. Abnormally high leakage from gates and valves may indicate distortion and warping precluding their use. Structural elements should be examined for buckling and damage. Operating equipment such as winches, hydraulic systems, control systems and their support structures, such as spillway bridge decks and spillway piers, should be inspected for any damage that may render the gates or lifting equipment inoperable. Similarly the condition of backup power supplies should be included in the post earthquake inspection schedules.

Penstocks

In some cases penstock failure or significant leakage from penstocks may lead to erosive damage to an earth dam downstream face or its toe that has safety implications for the dam. The condition of these penstocks and their controlling intake gates should be inspected to confirm satisfactory conditions.

APPENDICES

APPENDIX 1 – MODIFIED MERCALLI INTENSITY SCALE OF 1931 (Abridged)[1]

Intensity No.	Event
I	Not felt except by a very few persons under especially favourable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeable indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by a few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc, broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

[1] For complete details on this intensity scale, see BSSA, vol.3, p.277-283, Wood & Neumann, 1931.

X	Some well-built wooden structures destroyed, most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

NOTE: The MMI scale is still used by many countries as the default intensity scale but it is by no means the only scale used. Some European countries believe that the MMI scale is outdated.

The MMI scale is included here as an example of an intensity scale and each country should use whatever scale is accepted in their country. They are all similar in their purpose however.

APPENDIX 2 – EARTHQUAKE ALARM SYSTEMS

United States of America

Shake maps are generated automatically following moderate and large earthquakes in California, Nevada, Utah, Oregon, Washington and Alaska, USA.

They are preliminary ground shaking maps, normally posted within minutes of the earthquake. Separate maps provide:

- Peak horizontal ground acceleration in contours of 0.1g.
- Peak horizontal ground velocity in contours of cm/s.
- An instrumentally-derived, estimated Modified Mercalli Intensity in colored bands.
- Spectral response at periods of 0.3, 1.0 and 3.0 seconds in 0.1g contours.

A typical estimated peak ground acceleration map is shown in Fig. 2.1.

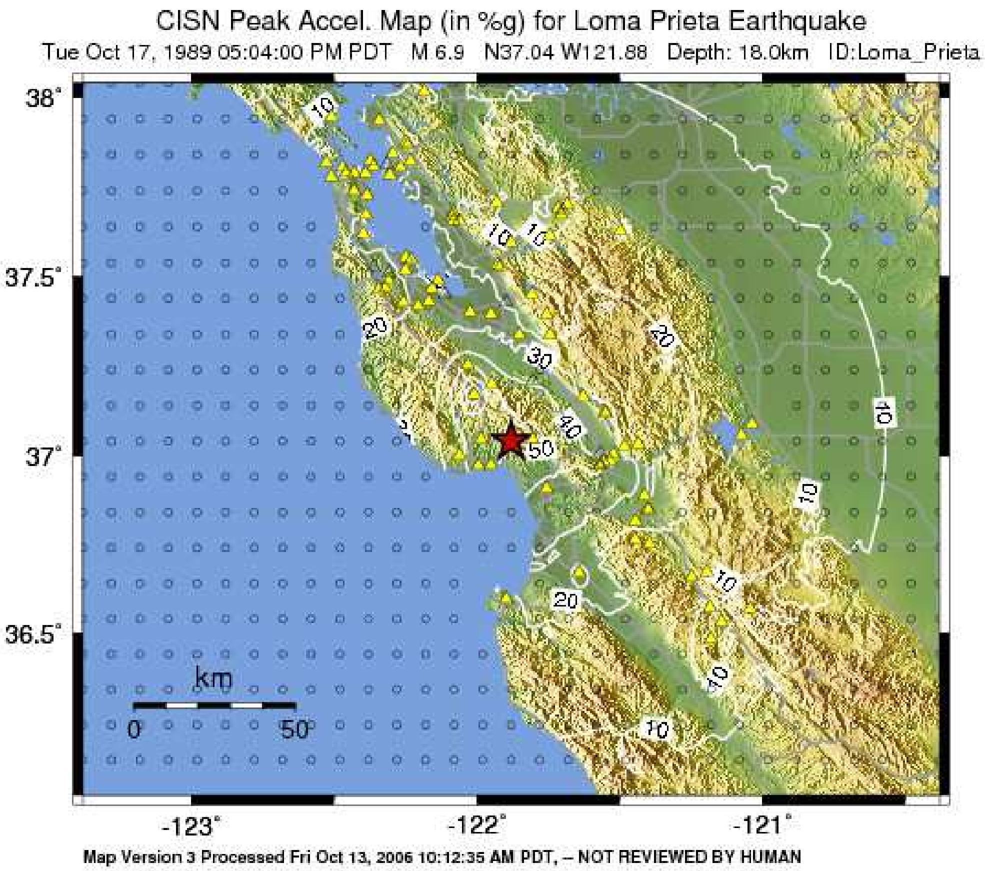


Fig. 2.1: Map showing contours of peak ground acceleration for the magnitude 6.9 Loma Prieta earthquake in California

The instrumentally derived intensity map type makes it easier to relate the recorded ground motions to the expected felt and damage distribution. It is based on a

To the extent possible the maps are based on accelerations measured at real time strong motion stations. In order to stabilize contouring and minimize the misrepresentation of the ground motion pattern due to data gaps, these data are augmented by predicted values in areas without stations. Using the epicenter and magnitude, peak ground motion amplitudes are estimated from relevant attenuation curves. As the real-time station density increases, the need for this augmentation will decrease.

Following earthquakes larger than magnitude 5.5, the spectral response maps are made. Response spectra portray the response of a damped, single-degree-of-freedom oscillator to the recorded ground motions. For each station, the value used is the peak horizontal value of 5% critically damped pseudo-acceleration.

The base maps are shaded relief maps that include cities, major highways, etc. Major faults, the epicenter and the strong motion recording sites station are shown, as are the locations where acceleration and velocities were predicted to fill in gaps are identified.

When viewing the peak ground motion maps using a Javascript-enabled browser, additional information about the earthquake epicenter and recording seismic stations can be viewed. The earthquake information includes the event date, time, location coordinates in degrees latitude and longitude, and hypocentral depth in kilometers. The station information includes the station code and name, the agency that manages the station, the station location coordinates in degrees latitude and longitude, and the peak acceleration and velocity values for each component of ground motion.

ShakeCast, short for ShakeMap Broadcast, is a fully automated system developed by the U.S. Geological Survey (USGS) to utilize ShakeMap in post-earthquake emergency response. The software automatically downloads a newly released ShakeMap and compares the measured ground motions against fragility levels pre-set for engineering structures. ShakeCast (version 1) allows three levels of fragilities to be set; damage unlikely (green alert), damage possible (yellow alert), and damage likely (red alert). ShakeCast can use any of the ground motion parameters currently transmitted by ShakeMap to specify fragilities. The software immediately notifies responsible personnel of the earthquake and the shaking level experienced at the facility via email or cell phone.

Australia

Many major dam owners in Australia rely on intelligent systems to provide notification to them of earthquake occurrences and reports setting out recommended response actions. Different approaches have been adopted for the system response by the different dam owners but the generic approach is as follows.

The priority of implementing response actions for dams is usually dependent on three key factors, being:

- The peak ground acceleration or intensity experienced at the individual dams.
- The susceptibility of the individual dams to earthquake shaking.
- The consequences of the failure of the dam.

The first factor can be calculated by a system as described above.

The second factor is determined based on the capability of the dam to resist seismic load. This factor can be based on historical evidence regarding damage to particular classes of dams. For example, the factor would be high for homogenous or hydraulic fill earthfill embankments and low for arch dams.

The third factor is just a measure of the consequences of a dam failure and could be simply based on the hazard rating for the dam.

By assigning numerical values to the individual factors and combining the factors (e.g. product of all three) an overall priority score is derived. For all dams that have experienced a MMI of 4 or greater, a priority score is determined and sorted in descending order to establish a recommended prioritized inspection program.

The priorities can be grouped into various categories with different responses assigned to each category. One current system has adapted the following response categories:

Response Level	**Likely Impact ***	**Response Required**
A	Less than MMI 4.	Inspect dam at next routine inspection.
B	MMI 4	Inspect dam within 18 hours.
C	MMI 5	Inspect dam within 6 hours.
D	MMI 6	Inspect dam immediately.
E	MMI 7 or greater	Inspect dam immediately.

***** *The above table has been simplified and is based on factor 1 only, i.e. the intensity experienced at the dam.*

An earthquake report is generated (automatically) and can be faxed, emailed, SMS messaged or verbally communicated by phone to all required recipients.

The report would typically provide the following information:

- Earthquake details (time, location, magnitude, etc).
- General earthquake impacts expected (i.e. estimated intensities at varying radii from the epicenter).
- Inspection resources required on priority basis.

A typical earthquake report is included in Appendix 3. Different reports can be produced, or the report can be sub-divided according to the different operational areas that may exist within an organisation.

The report recommendations provide intelligence that can be used in conjunction with other site-specific data and knowledge to implement a rapid, effective and cost efficient earthquake response inspection program for a group of dams, particularly where dams are not usually manned 24 hours per day, 7 days per week.

Japan

Two agencies play a role in Japan in publishing maps of ground shaking.

The Japan Meteorological Agency (JMA) usually within a few minutes reports on the seismic intensity of the earthquake for severely shaken areas. A map is reported immediately after the event on the website. It is also promptly broadcasted on TV and radio. The intensity scale is calculated from the time histories recorded of earthquake motions and reflects the peak values of velocity and acceleration. A typical map is shown in Fig. 2.2 below.

The National Research Institute for Disaster Prevention and Earth Science has four different strong motion networks established:

a) K-NET is a network of seismographs, installed at approximately 1,000 locations nationwide, capable of capturing and recording strong and damaging seismic motions.

b) Hi-Net has 700 stations nationwide, capable of detecting very weak ground motions unnoticed by humans. Seismometers are installed in a borehole at a depth of 100 m or more to avoid surface ground noise.

c) Pairs of strong motion seismographs are also installed on and beneath the ground at Hi-Net sites to form the KiK-net system.

d) F-Net is composed of more than 70 stations nationwide and is capable of detecting very weak to strong ground motions in broadband frequency range. Strong motion data from the first three networks above have been used to evaluate the risk of earthquake damage on Japan islands.

If an earthquake has occurred, the Institute posts Peak ground acceleration (PGA) and peak ground velocity (PGV) contour maps within an hour on their website.

Arrangements can be made with individual owners for notice of seismic intensities to be provided over mobile/cellular phones. Such notification, together with measured data from accelerometers installed in most dams can be used in decision making regarding implementing dam inspections.

The dam operator would normally be required to inspect dams within 8 hours if the PGA is greater than 25 cm/s^2 or exceeds a value of 4 on the JMA Intensity Scale, which is equivalent to a MMI of 6. A primary (initial) and secondary inspection are carried out with the primary results reported to the Supervisory Office within 3 hours and the secondary results within 24 hours. In the case of the PGA being less than 80 cm/s^2, the JMA intensity is less than or equal to 4 and if no damage is detected in the primary inspection, no secondary inspection is required.

In August 2006 commenced a new service "Emergency Earthquake Advisory" as a trial that records tremors at sites in the vicinity of the epicenter and reports it to agencies in charge of disaster prevention, traffic organizations and others before the arrival of the seismic wave. This system is expected to reduce the earthquake damage in the future.

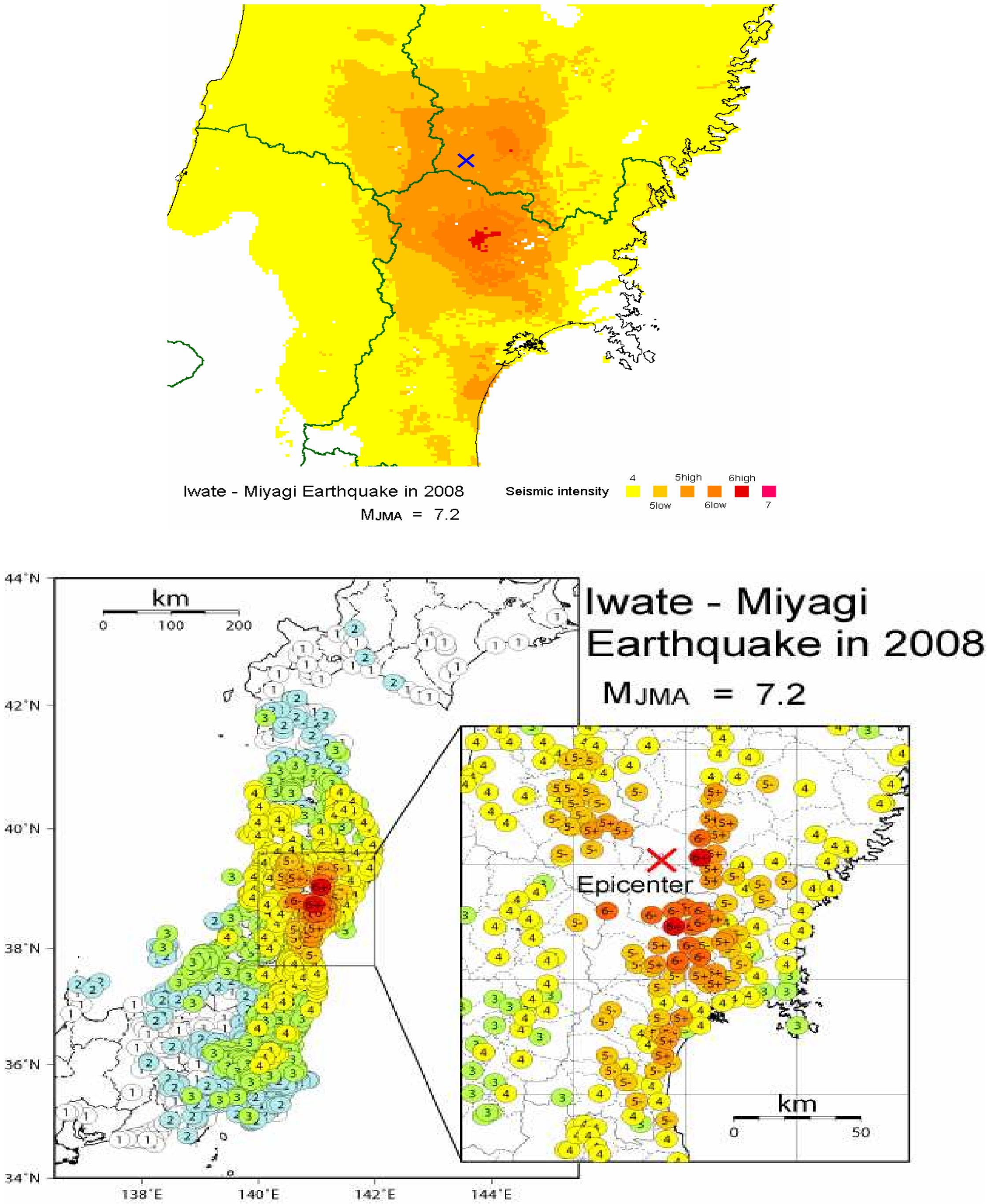


Fig. 2.2: Example of JMA intensities following the magnitude 7.2 Iwate-Miyagi earthquake in Japan (June 14, 2008)

APPENDIX 3 – EARTHQUAKE ALARM REPORT

Date:	YYYY-MM-DD	Time:	
Longitude:		Latitude:	
Depth:		Magnitude:	

General Outcomes

- The intensity at the epicentre would be about MMI 5.
- Intensities exceeding MMI 4 with the earthquake being strongly felt by most people can be expected to a distance of 30 km.
- Intensities exceeding MMI 2 and the possibility that the earthquake will be felt by some people can be expected to a distance of 120 km.
- Possibility of damage very low at *[town or place]* (14 km, MMI 5).
    - Sleeping people wakened, hanging objects swing.
- Damage highly unlikely at *[town or place]* (48 km, MMI3).
    - Vibrations felt but may not be recognised as an earthquake at first.

Specific Outcomes

- XXXXX Dam (16 km, MMI 5)
    - Damage to well-built structures unlikely.
- XXXXX Dam (31 km, MMI 4)
    - Probability of damage extremely low.

Tasks in Priority Order

- Contact XXXX on *[contact number]* to tell them to perform seismic response level C (inspect within six hours) at XXXXX Dam.
- Contact XXXX on *[contact number]* to tell them no immediate action is necessary and to perform seismic response level A (inspect at next routine inspection) at XXXXX Dam.
- Telephone XXXXX on *[contact number]* to advise that the above notifications have been made.

No other tasks prescribed.

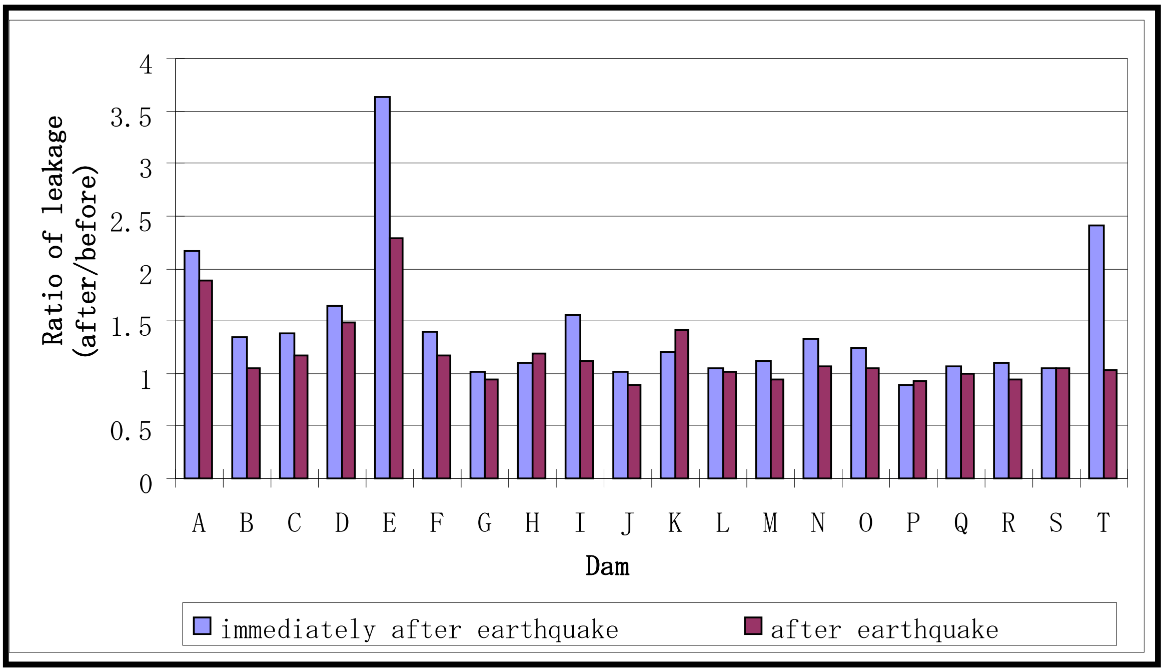
Note: The Outcomes and Tasks provided by this program depend on the attenuation function selected, and the Importance, Vulnerability and Priorities assigned by the user.

Unless specifically provided, this program does not consider site amplification by soft sediments or topography. Note that a preliminary earthquake epicentre, depth and magnitude may have errors which affect expected outcomes.

APPENDIX 4 – EFFECTS OF EARTHQUAKES ON LEAKAGE AND UPLIFT PRESSURES

Earthquakes often affect the leakage and pore pressures within the dam body or foundation during and after the event. Such effects can be experienced at very long distances from large earthquakes.

Figures 4.1 and 4.2 show the short-term variation of leakage in the body or foundation of twenty dams in Japan. The ratio of leakage after and before the earthquake is plotted for seven concrete gravity, eight rockfill, and five earthfill dams. Of the 20 dams, an increase in leakage was observed at 19 dams. The increase was more than 20% at 11 dams. 17 of the 19 dams with increased leakage showed that the increase of leakage decreased within a fortnight. At 11 of the 20 dams the ratio a fortnight after the event was in the range 0.9 to 1.1. At 4 dams the ratio was greater than 1.2. The greatest ratio was experienced at a concrete gravity dam where the leakage increased from a small value of 11 l/min to 39 l/min. The leakage occurred through construction joints, transverse joints, and foundation drain holes. The maximum leakage was observed at Dam 'M' which increased from 404 to 452 l/min immediately after the earthquake and reduced to 381 l/min 14 days after the earthquake.



Note: 'Immediately after earthquake' means within two days. 'After earthquake' means from several days to a fortnight after the earthquake.

Fig. 4.1: Earthquake induced variations in leakage of dams in Japan

Table 1: Dam type and magnitude of earthquakes included in Fig 4.1

Dam	Type	Earthquake (Magnitude)	Ref
A	TE	Niigata Earthquake of Oct 23, 2004 (M6.8)	1
B	TE	"	
C	ER	Tokachi Earthquake of Sep 26, 2003 (M8.0)	2
D	PG	"	
E	PG	"	
F	ER	"	
G	PG ER	Miyagi Earthquake of May 26, 2003 (M7.1)	3
H	PG ER	"	
I	ER	"	
J	ER	"	
K	ER	"	
L	ER	Sanriku-haruka Earthquake of Dec 28, 1994 (M7.5)	4
M	ER	"	
N	PG	"	
O	PG	Southwest Hokkaido Earthquake of July 12, 1993 (M7.8)	5
P	TE	"	
Q	TE	"	
R	TE	"	
S	ER	"	
T	TE	East Chiba Earthquake of Dec 17, 1987 (M6.7)	6

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1. National Institute for Land and infrastructure Management Report on Niigata Earthquake, 2006.
2. National Institute for Land and infrastructure Management Report on Tokachi Earthquake, 2004.
3. National Institute for Land and infrastructure Management Report on Miyagi Earthquake, 2003.
4. Nakamura et al.: Engineering for Dams No.106, 1995
5. Nakamura et al.: Engineering for Dams No.95, 1993
6. Matsumoto et al.: Engineering for Dams No.25, 1988

Figure 4.2 shows the long-term variation of leakage in Kamafusa dam, which was subjected to the 1978 Miyagi earthquake (M=7.4). Both the leakage from the foundation drain holes, construction joints, and transverse joints increased after the event. The leakage from the foundation decreased within a few months but did not return to the before earthquake leakage rate. However, the leakage from the joints returned to almost nil.

Figure 4.3 indicates the relationship between water level and pore pressure in the foundation of Hitokura dam, which was shaken by the 1995 Kobe earthquake (M=7.3). The peak acceleration in the bottom gallery and at dam crest was 0.19 and 0.49 g, respectively. The pore pressure level increased by 5 m after the event and it took more than 2 years to return to the before earthquake value.

These case studies show that leakage and pore pressures often change as a result of ground shaking. Usually they increase after an earthquake. However, in most cases the increase is only temporary and will decrease or become stable over time. It may last from several days to a few years until a stable condition is reached.

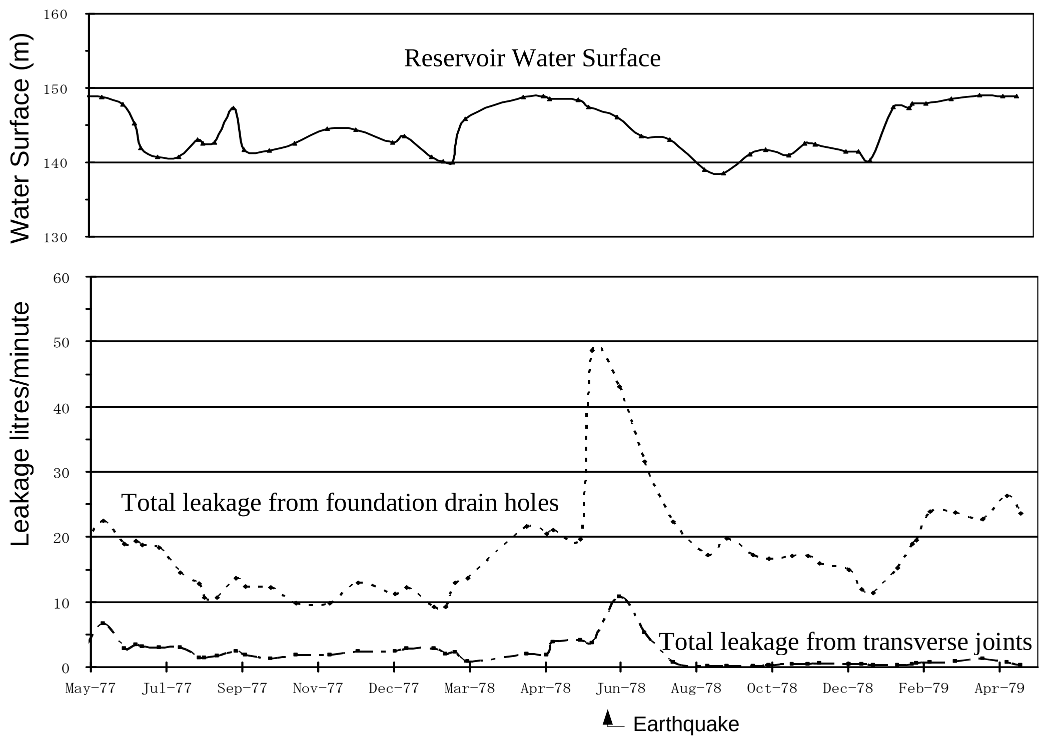

Fig 4.2: Variation of leakage in Kamafusa dam before and after the Miyagi earthquake (Ref. Matsumoto et al., "Miyagi Earthquake of 1978", PWRI Report No 159, 1983)

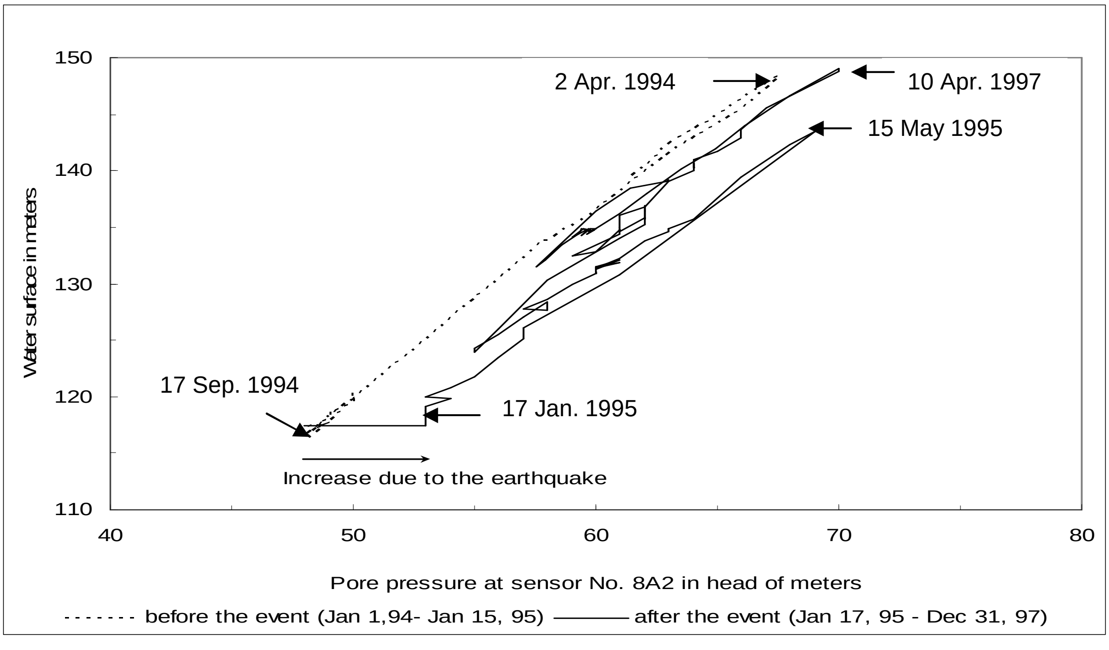

Fig. 4.3: Variation of pore pressure in Hitokura dam due to the 1995 Kobe earthquake

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APPENDIX 6 – INSPECTION CHECKLISTS

General Notes

Fully describe all observations using words and sketches as appropriate.

If an item is not applicable, so indicate.

Record the fact if nothing is found to be wrong or damaged.

State if inspection was not done, or not possible to do.

The following inspection checklists should be modified for actual dams by reviewing plans, specifications and reports on the dams; inspecting the dams and discussing them with their operators.

6.1 INSPECTION CHECKLIST FOR ALL DAMS

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Date of Inspection .... Time ....

Operational Status at Time of Inspection

Reservoir water surface elevation ....

Releases ....

Weather conditions ....

Water in storage ....

Reservoir rise during earthquake ....

Inspection Team

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Description of earthquake as felt at site (refer to Mercalli Scale)

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6.2 INSPECTION CHECKLIST FOR EMBANKMENT DAM

DAM

Upstream Face

- Slide movements ....
- Erosion – breaching ....
- Cracks ....
- Sinkholes ....
- Settlement ....
- Displacement ....
- Slope protection ....
- Debris ....
- Unusual conditions ....

Crest

- Surface cracking ....
- Settlement ....
- Lateral movement (alignment) ....
- Camber ....

Parapets, Kerbs, Railings

- Deformation ....
- Lateral Movement (alignment) ....
- Cracking ....

Downstream Face

- Erosion – breaching ....
- Cracks ....
- Sinkholes ....
- Slide movements ....
- Settlement ....
- Displacement ....
- Unusual conditions ....

Downstream of the dam

- Boils ....
- Springs ....
- Sinkholes ....

INSPECTION CHECKLIST FOR EMBANKMENT DAM

DAM (cont'd)

Abutments
- Cracks, open joints ________
- Erosion ________
- Sinkholes ________
- Slide movements ________
- Unusual conditions ________

Drainage/Inspection Adits
- Lighting, ventilation ________
- Total drain flow ________
- Individual drain flows ________
- Cracks ________
- Seepage ________
- Joint offsets, openings, spalling ________
- Rockfalls ________

Seepage, Toe Drains, Galleries, Adits, Relief Drains
- Locations ________
- Estimated flow(s) ________
- Change in flow ________
- Clearness
  - Colour ________
  - Fines ________

Methods of flow measurements ________

Condition of measuring devices ________

Records ________

Performance Instruments
- Piezometers ________
- Surface settlement points ________
- Internal movement devices ________
- Inclinometers ________
- Reservoir level gage ________
- Seismic instruments ________

INSPECTION CHECKLIST FOR EMBANKMENT DAM

DAM (cont'd)

Special Items

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INSPECTION CHECKLIST FOR EMBANKMENT DAM

SPILLWAY

Approach Channel

- Debris ____________________
- Slides above channel ____________________
- Side slope stability ____________________
- Slope protection ____________________
- Log boom ____________________

Control Structure

- Slides above structures ____________________
- Debris ____________________
- Gates
  - Observed operation ____________________
  - Alignment ____________________
  - Anchorages ____________________
  - General condition ____________________
- Hoists or operating stems
  - Observed operation ____________________
  - Signs of movement ____________________
  - Anchorages ____________________
  - General condition ____________________
- Controls
  - Observed operation ____________________
  - Signs of movement ____________________
  - Anchorages ____________________
  - General condition ____________________
- Power Supply
  - Primary ____________________
  - Emergency ____________________

Crest

- Cracks or areas of distress ____________________
- Signs of movement ____________________

SPILLWAY (cont'd)

Walls

- Movement (offsets) ....
- Cracks or areas of distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....
- Backfill settlement ....

Apron

- Movement (offsets) ....
- Cracks or areas of distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....

Bridge

- Pier alignment and condition ....
- Structural condition of slab and beams ....
- Bearings alignment and condition ....

Cranes

- Observed operation ....
- General condition ....
- Structural distortion ....
- Anchorages ....

Chute

- Debris ....
- Slides above chute ....
- Walls
  - Movement (offsets) ....
  - Cracks or areas of distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....

INSPECTION CHECKLIST FOR EMBANKMENT DAM

SPILLWAY (cont'd)

Backfill settlement ....

Floor

- Movement (offsets) ....
- Cracks or areas of distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....
- Drainage gallery
  - Ventilation, lighting ....
  - Misalignment ....
  - Joint spalling or opening ....
  - Cracking ....
- Drains
  - Amounts of flow ....
  - Locations of flowing drains ....

Stilling Basin

- Debris ....
- Slides above basin ....
- Walls
  - Movement (offsets) ....
  - Cracks or areas of distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Backfill settlement ....
- Floor (if visible)
  - Movement (offsets) ....
  - Cracks or areas of distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Erosion ....

INSPECTION CHECKLIST FOR EMBANKMENT DAM

SPILLWAY (cont'd)

Debris ....

Erosion ....

Slides above channel ....

Side slope stability ....

Slope protection ....

Vegetation or other obstructions ....

Special Items

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INSPECTION CHECKLIST FOR EMBANKMENT DAM

OUTLET WORKS

Discharge
- Turbidity ....
- Solids ....

Approach Channel (if visible)
- Debris ....
- Slides above channel ....
- Side slope stability ....
- Slope protection ....

Intake Structure
- Slides above structure ....
- Debris ....
- Trash racks ....

Conduit or Tunnel
- Ventilation, lighting ....
- Change in seepage ....
- Joint openings ....
- Concrete spalling ....
- Steel liner bulges ....
- Rockfalls ....

Valves or Gates and their Operators
- Observed operation ....
- General condition
  - Signs of movement ....
- Anchorages ....
- Controls
  - Observed operation ....
  - Signs of movement ....
  - Anchorages ....
  - General condition ....
  - Remote operation functions ....

INSPECTION CHECKLIST FOR EMBANKMENT DAM

OUTLET WORKS (cont'd) ....

- Power Supply
  - Primary ....
  - Emergency ....
- Cranes
  - Observed operation ....
  - General condition ....
  - Structural distortion ....
  - Anchorages ....

Bulkheads

- General condition ....
- Seals ....

Chute

- Debris ....
- Slides above chute ....
- Walls
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Backfill settlement ....
- Floor
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....

Stilling Basin

- Debris ....
- Slides above basin ....

INSPECTION CHECKLIST FOR EMBANKMENT DAM

OUTLET WORKS (cont'd) ....

- Walls
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Backfill settlement ....
- Floor (if visible)
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Erosion ....

Outlet Channel

- Debris ....
- Slides above channel ....
- Side slope stability ....
- Slope protection ....
- Vegetation or other obstructions ....

Special Items

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INSPECTION CHECKLIST FOR EMBANKMENT DAM

RESERVOIR

Landslides

- Individual designations ....
- Locations ....
- Conditions ....

Blocked inflows ....

Log Boom ....

Special Items

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ACCESS ROADS

Roadways

- Obstructions ....
- Condition of pavement ....

Bridges

- Structural condition of deck slabs and beams ....
- Bearings alignment and condition ....
- Pier alignments and condition ....
- Foundation conditions ....

Special Items

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6.3 INSPECTION CHECKLIST FOR CONCRETE DAM

DAM

Upstream Face

- Cracks ....
- Joints, offsets, openings, spalling ....

Crest

- Alignment of walls, edges ....
- Cracks ....
- Joint openings, offsets, spalling ....
- Parapet wall condition ....
- Lighting ....

Downstream Face

- Cracks ....
- Joint offsets, openings, spalling ....
- Seepage ....

Downstream Toe

- Seepage ....
- Scour, undercutting ....
- Cracks, other distress ....

Downstream of dam

- Boils ....
- Springs ....
- Sinkholes ....

Galleries

- Lighting, ventilation ....
- Total drain flow ....
- Individual drain flows ....
- Cracks ....
- Seepage ....
- Joint offsets, openings, spalling ....

Performance Instruments

- Piezometers ....
- Surface monuments ....
- Pendulums ....

INSPECTION CHECKLIST FOR CONCRETE DAM

DAM (cont'd)

- Reservoir level gage ....
- Seismographs ....

Special Items

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ABUTMENTS

Drain flows ....

Landslides ....

Seepage ....

Seepage locations ....

Drainage/Inspection Tunnels

- Lighting, ventilation ....
- Total drain/seepage flow ....
- Individual drain flows ....
- Cracks ....
- Seepage ....
- Joint offsets, openings, spalling ....
- Rockfalls ....

Performance Instruments

- Piezometers ....
- Surface monuments ....
- Extensionometers ....

Special Items

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INSPECTION CHECKLIST FOR CONCRETE DAM

SPILLWAY

Approach Channel

- Debris ....
- Slides above channel ....
- Side slope stability ....
- Slope protection ....
- Log boom ....

Control Structure

- Slides above structures ....
- Debris ....
- Gates
  - Observed operation ....
  - Alignment ....
  - Anchorages ....
  - General condition ....
- Hoists or operating stems
  - Observed operation ....
  - Signs of movement ....
  - Anchorages ....
  - General condition ....
- Controls
  - Observed operation ....
  - Signs of movement ....
  - Anchorages ....
  - General condition ....
- Power Supply
  - Primary ....
  - Emergency ....

Crest

- Cracks or areas of distress ....
- Signs of movement ....

Walls

- Movement (offsets) ....

INSPECTION CHECKLIST FOR CONCRETE DAM

SPILLWAY (cont'd)

- Cracks or areas of distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....
- Backfill settlement ....

Apron

- Movement (offsets) ....
- Cracks or areas of distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....

Bridge

- Pier alignment and condition ....
- Structural condition of slab and beams ....
- Bearings alignment and condition ....

Cranes

- Observed operation ....
- General condition ....
- Structural distortion ....
- Anchorages ....

Chute

- Debris ....
- Slides above chute ....
- Walls
  - Movement (offsets) ....
  - Cracks or areas of distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Backfill settlement ....

INSPECTION CHECKLIST FOR CONCRETE DAM

SPILLWAY (cont'd)

Floor

- Movement (offsets) ....
- Cracks or areas of distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....
- Drainage gallery
  - Ventilation, lighting ....
  - Misalignment ....
  - Joint spalling or opening ....
  - Cracking ....
- Drains
  - Amounts of flow ....
  - Locations of flowing drains ....

Stilling Basin

- Debris ....
- Slides above basin ....
- Walls
  - Movement (offsets) ....
  - Cracks or areas of distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Backfill settlement ....
- Floor (if visible)
  - Movement (offsets) ....
  - Cracks or areas of distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Erosion ....

INSPECTION CHECKLIST FOR CONCRETE DAM

SPILLWAY (cont'd)

Outlet Channel

- Debris ....
- Erosion ....
- Slides above channel ....
- Side slope stability ....
- Slope protection ....
- Vegetation or other obstructions ....

Special Items

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OUTLET WORKS

Discharge

- Turbidity ....
- Solids ....

Approach Channel (if visible)

- Debris ....
- Slides above channel ....
- Side slope stability ....
- Slope protection ....

Intake Structure

- Slides above structure ....
- Debris ....
- Trash racks ....

Conduit or Tunnel

- Ventilation, lighting ....
- Change in seepage ....
- Joint openings ....
- Concrete spalling ....
- Steel liner bulges ....

INSPECTION CHECKLIST FOR CONCRETE DAM

OUTLET WORKS (cont'd)

Rockfalls ....

Valves or Gates and their Operators

- Observed operation ....
- General condition
  - Signs of movement ....
- Anchorages ....
- Controls
  - Observed operation ....
  - Signs of movement ....
  - Anchorages ....
  - General condition ....
  - Remote operation functions ....
- Power Supply
  - Primary ....
  - Emergency ....
- Cranes
  - Observed operation ....
  - General condition ....
  - Structural distortion ....
  - Anchorages ....

Bulkheads

- General condition ....
- Seals ....

Chute

- Debris ....
- Slides above chute ....
- Walls
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....

INSPECTION CHECKLIST FOR CONCRETE DAM

OUTLET WORKS (cont'd)

- Joint spalling or opening ....
- Drains ....
- Backfill settlement ....

Floor

- Movement (offsets) ....
- Cracks, other distress ....
- Settlement ....
- Joint spalling or opening ....
- Drains ....

Stilling Basin

- Debris ....
- Slides above basin ....
- Walls
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Backfill settlement ....
- Floor (if visible)
  - Movement (offsets) ....
  - Cracks, other distress ....
  - Settlement ....
  - Joint spalling or opening ....
  - Drains ....
  - Erosion ....

Outlet Channel

- Debris ....
- Slides above channel ....
- Side slope stability ....
- Slope protection ....

INSPECTION CHECKLIST FOR CONCRETE DAM

OUTLET WORKS (cont'd)

Vegetation or other obstructions ______________________

Special Items

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RESERVOIR

Landslides

Individual designations ______________________

Locations ______________________

Conditions ______________________

Blocked inflows ______________________

Log Boom ______________________

Special Items

____

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____

____

ACCESS ROADS

Roadways

Obstructions ______________________

Condition of pavement ______________________

Bridges

Structural condition of deck slabs and beams ______________________

Bearings alignment and condition ______________________

Pier alignments and conditions ______________________

Foundation conditions ______________________

INSPECTION CHECKLIST FOR CONCRETE DAM

ACCESS ROADS (cont'd)

Special Items