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CHALLENGES IN HIGH TAILINGS DAMS: A REVIEW OF KEY FACTORS FOR A CORRECT PERFORMANCE EVALUATION UNDER HIGH CONFINEMENT PRESSURES

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ABSTRACT

Tailings dams are live infrastructures, as they constantly evolve along its operational life, increasing in height and capacity, according to the deposition tailings plan. Driven by new environmental requirements which restrict the use of disposal areas for new tailings deposits and the increase of waste volume produced on the mining operation, current tailings dams have increased its size far beyond the maximum height and capacity considered in the original design. Many of those dams originally did not consider the geomaterials behavior under these higher confining stresses. Thus, high stresses related phenomena such as particle breakage of coarse granular soil materials, reduction on drainage system capacity, and transition from dilative to contractive behavior of dam material and foundation soil, including the starter dam, may be neglected when the technical studies that support new rises are evaluated, even though they are key factors ensuring the global stability of the deposit under these new conditions.

This work presents a broad review of the effects of high confining pressures in granular soil materials (tailings sand and rockfill) related to the dam, soil foundation and drains construction materials, its effects on shear strength and hydraulic conductivity, the reduction in drain capacity and the potential increase on phreatic levels.

Keywords: Tailings, High Confining Pressures, Geomaterials, Large Dams.

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1. INTRODUCTION

Currently, the design of tailings dams is constantly changing throughout the operational life of the dam. There are new requirements caused by the increase of waste volume produced by extension of the mine life and, also restrictions of disposal areas. Consequently, tailings dams have increased their size far beyond the maximum height considered in the original design. In many tailings dams, the original design did not characterize the geomaterials behavior under confining stresses higher than those expected for the dam maximum height, as it was considered at the beginning of the project. Thus, evaluation of high stress related phenomena such as particle breakage of granular soil materials, reduction on the drainage system capacity and transition from dilative to contractive behavior of the foundation soil have been neglected in the technical studies, even though they are key factors defining global stability of the dam.

This paper reviews and summarizes a brief selection of essential studies on tailings and geomaterials present in dams, in order to illustrate the effect of high confining pressures on them. Firstly, statics and cyclic behavior of sands are described, then some results are compared with results of an exhaustive laboratory program carried out on different sand tailings samples subjected to high confining pressures. For both cases, the Critical State Line (CSL) theory was used to characterize the materials and rationalize the main findings. In addition, new methodologies are described which are used in practice, such as the Critical State approach which is based on the state-parameter measured in situ and which is calibrated with laboratory tests.

On the other hand, rockfill behavior is summarized with focus on the phenomenon of particle breakage which occurs at high level stress, while the existing limitations of this knowledge base are identified. Also, drainage system design is analyzed focusing on a description of its components, the general design criteria used and the challenges arising at high pressures as the breakage of particles affects hydraulic conductivity due to the behavior of coarse granular materials.

Finally, soil foundation as failure mechanism is illustrated and analyzed through case studies such as Mount Polley and Cadia failures.

2. EFFECTS OF HIGH CONFINING PRESSURES IN GEOMATERIALS

2.1. Dam Materials (Tailings Sand and Rockfill)

2.1.1. Tailings Sands

After El Cobre Dam Failure (for more information see [1] and [2]), Chilean regulation, through the Decree N° 86, established several requirements for the design of tailings dams. The main contribution of the Decree was the identification and recognition of the importance of saturated sand zones and compaction in physical stability, that is, a low compaction effort used for wall construction would made it vulnerable to liquefaction, in presence of water [3] [4]. These issues were overcame by making crucial changes regarding sand tailings wall design, by forbidding the upstream construction method and by using centerline and downstream construction systems with gentler slopes (i.e. 4H:1V), which allowed a more uniform compaction from a compaction roller, while minimizing the effort after hydraulic placement. Other changes considered the inclusion of robust drainage systems in the dam design, while identifying it as a critical component of the dam physical stability, and a call for strict control in sand tailings generation through cycloning, focused mainly on the content of fines [3].

Verdugo [5] presented and interpreted the results of an extensive set of laboratory tests performed on copper tailings sand mixtures, having the same origin but with variable fines content. The results were interpreted by the author arguing that only two factors involved in the tailings sand resistance to liquefaction (used herein as a broad term, involving both the cyclic mobility and flow failure phenomena) could be controlled during the construction/operation of the tailings dam, which were a) compaction degree of the sand, and b) the content of fines. Later, Campaña et al. [6] [7], performed a comprehensive analysis of the behavior of four different copper tailings sands, having similar mineralogy (45-60% Quartz), subjected to high confining stresses. The main findings from both authors will be presented together, identifying whether the behavior of copper tailings sands differs at varying confining stresses. While the sands studied by both authors come from different origin, they were mainly composed of quartz and produced artificially by the crushing of rock, thus it is believed that the observed tendencies are comparable for the purpose of this present review.

Verdugo [5] concluded that the concept of relative density holds valid for tailings sand with non-plastic fine contents up to 50%, as small differences were found between the results of compaction obtained by vibration and by the Modified Proctor Test (Fig. 1a). Additionally, tailings sands achieved maximum and minimum void ratios which were higher and lower than those measured on natural sands, for varying content of fines (Fig. 1b).

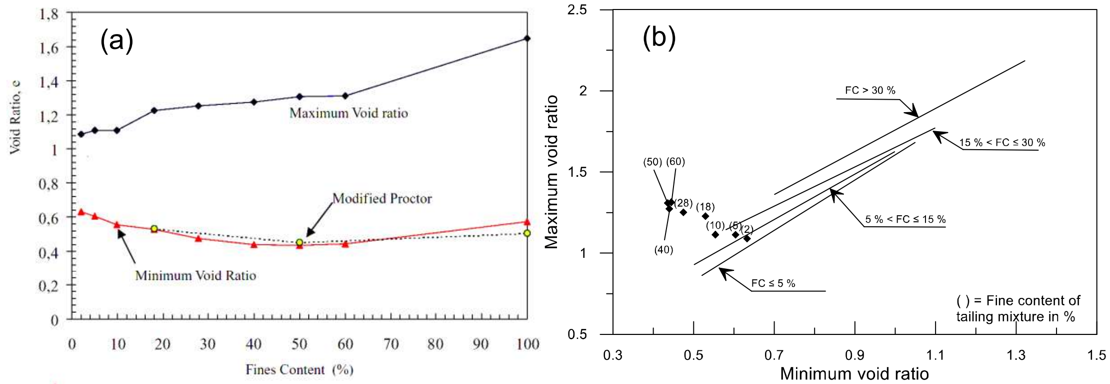

Fig. 1 – Void ratio relationships (a) Maximum and minimum void ratios as function of fines content (b) Maximum and minimum void ratios of tailings and natural sands *(*adapted from [5]).

On the topic of Cyclic Shear Resistance (CSR), according to Verdugo's test results, the CSR of the material decreases as the fine content increases, regardless of how small the fine content may be (Fig. 2a). While a sharp increase in cyclic strength is observed when increasing sample density above a threshold (DR ~ 50%) in samples with fine contents lower than 10%, mixture of sands with 18% to 28% of content of fines showed a more gradual increase (Fig. 2b) [3] in cyclic strength. On the other hand, for the four sands analyzed plus an additional quartz-based copper tailings sand, with a wide range of different content of fines, Bard et al. [8] found that, while a high scatter in CSR was seen for lower confining pressures ($\sigma_3' \leq 0.5\ \mathrm{MPa}$, Fig. 3a), at higher confining pressures the results aligned very closely and a major influence of the content of fines on the results was not observed (Fig. 3b) [8].

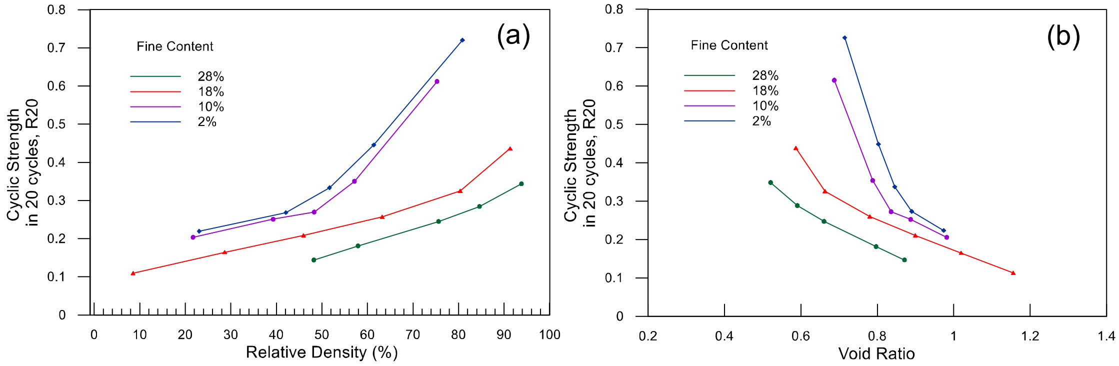

Fig. 2 – Cyclic Shear Resistance (a) R20 (cyclic strength in 20 cycles) as a function of relative density, for various fine contents (b) R20 as a function of void ratio, for varying fine contents (adapted from [5]).

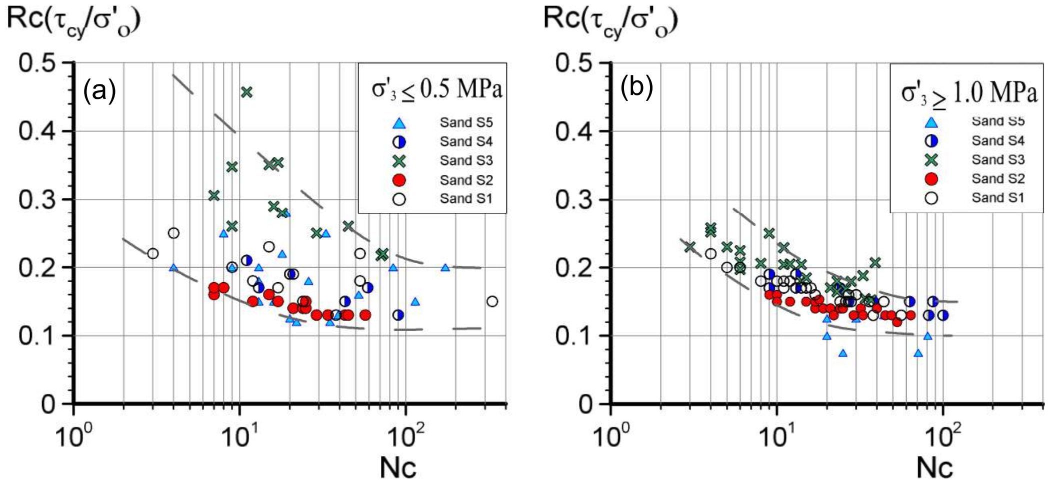

Fig. 3 - Comparison of Cyclic Shear Resistance for tailing sands (a) Confining pressure $\sigma'_3 \leq 0.5\ MPa$ (b) $\sigma'_3 \geq 1.0\ MPa$; KC = 1 [8]

Regarding the drained steady state strength, Verdugo [5] found that all the steady state test results aligned on a unique line in the q-p’ plane, associated with an angle of friction φ’ equal to 35°, the content of fines having no impact on the residual drained strength. The fines content did impact the compressibility of the material, as observed by the movement of the steady state line of the sands for varying content of fines (Fig. 4), while maintaining the same slope. Campaña et al. [7] obtained similar results, with most of the steady state from CIU and CID tests being characterized by friction angles (φ’) between φ = 32° and φ = 36°, not observing an appreciable impact of higher confining stresses, which was explained by the hardness and angularity of the sands. Regarding the steady state line in the e-p’ plane, a similar trend was found in [6], where the best fit of steady state test results, grouped by their content of fines, showed that compressibility increased with higher fines. Additionally, at higher confining pressures all best fit lines tend to converge into a single critical state line, independently of the content of fines.

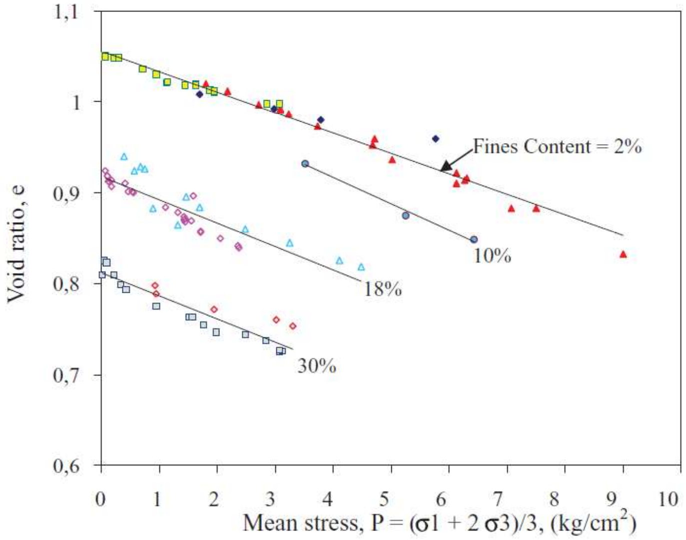

Fig. 4 – Steady state lines for varying fine contents in copper tailing sands [5]

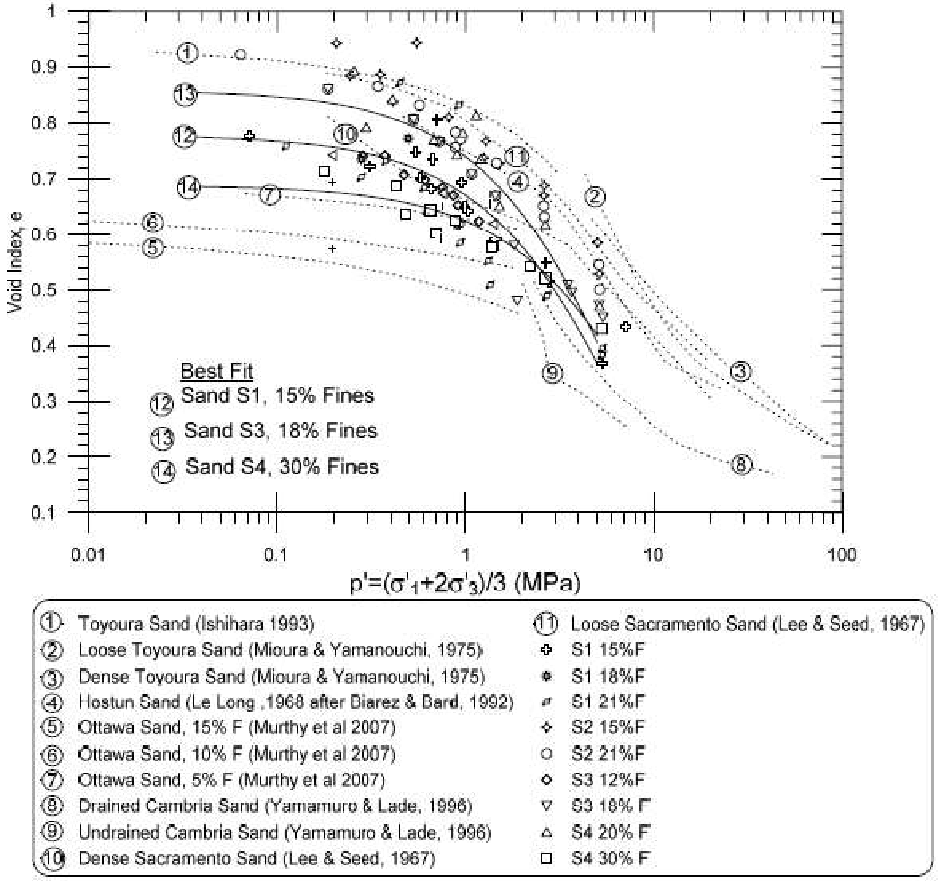

Fig. 5 – Steady state results for tailing sands S1 to S4 and comparison with results published in literature for natural sands [7]

Finally, regarding degradation of deformation modulus, in [5] a review of existing data ([9] and [10]) showed that copper tailings sand show a lower degradation of the modulus and an increasement of the damping, when it is compared with natural sands at the same strain. In [7] an analysis of the tangent module Ei at large deformations, obtained using an hyperbolic fit, was performed from CID triaxial test results as a function of confinement pressure and void ratio. All test results seem to be aligned along a narrow band, the content of fines having apparently no influence on the results (Fig. 6).

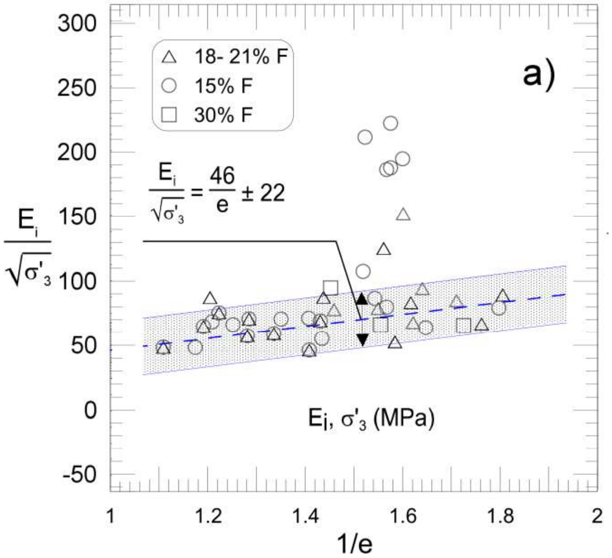

Fig. 6 – Normalized Ei variation by confining stress in CID triaxial test [7]

2.1.2.1 Considerations for an adequate tailings sands characterization program in the evaluation of in situ conditions

Extensive laboratory programs for sands characterization are incredibly useful and mandatory during the design phase. Differences between design and operation/construction are certainly expected mainly due, but not limited to, changes in mineralogy of the mined rock, segregation during hydraulic placement of the sands, and problems in QA/QC during operation and/or construction.

While in-situ testing of the tailings deposit wall and impoundment by the mine owner is desired, to advert any negative trend in the operation of the deposit, as those indicated before, it is mandatory in the case of expansion projects to assess the state of the tailings dam wall (and its impoundment), as the new designers are becoming responsible of the whole deposit physical stability and as the design phase is an appropriate stage to identify negative trends and design adequate corrective measures.

Careful laboratory testing of specimens extracted in-situ would be ideal, yet even at the most cautious handling of samples significant densification has been observed and measured [12].

While corrections for densification could be developed, the current trend of tailings characterization have been adopting characterization through the Critical State approach proposed by Been & Jefferies [11], which consist in [12]:

- Determine the state of the soil in-situ (‘state’ or ‘state parameter’ defined as the distance of the material at its current tensional state, in the e-p’ plane, to its critical state line, more details in [11]); in the case of tailings sands, CPTs (Cone Penetration Test) are recommended due to their continuous measuring, independency of operator influence on the results and availability.
- Measure the engineering parameters used in design as a function of state, through laboratory testing of remolded samples.
- Carry out an appropriate analysis to extrapolate engineering parameters to the in-situ material, using CPT data inversion through numerical analysis.

The aforementioned approach has been used successfully in the in-situ characterization of offshore hydraulic fills [13] while also becoming a key component in recent investigations of Tailings Storage Facility (TSF) failures ([14] and [15]) [16]. While promising, there are still issues to be resolved regarding tailings sand characterization. As shown by Verdugo [5] (Fig. 4), the content of fines in tailings sands influences the position of the CSL notably (compressibility). This content is expected to vary due to normal operational fluctuations and through segregation of fines in depth, which complicates the analysis since a continuous profile of the content of fines is not expected, while desirable.

On the other hand, issues regarding the CSL definition in laboratory could arise, as identified by Reid et al. [16]. The authors performed a round robin program of laboratory measurement of the CSL of a gold tailing sample, in order to evaluate the reliability and reproducibility of various forms of testing used by geotechnical laboratories. Reid results showed that the main difficulties arose in the correct measurement of the void ratio after tests. Thus, while laboratories that use the EOTSF technique (end of test soil freezing, [17]) to measure void ratio, showed a good agreement in the CSL measurement (+/- 0.04 variation in e for each confining stress tested), a high dispersion in the results was seen for the rest of laboratories results. Clearly the EOTSF technique is not available everywhere, yet efforts must be made to standardize the CSL determination procedure, for it to be completely reliable in site characterization. High confining pressures were not analyzed in [16].

2.1.2. Rockfill

Rockfill is a granular material, usually derived from the mineral exploitation process. For this reason, it has the potential to be used as construction material for a tailings dam (costs, transportation, strength). The coarse particle size of rockfill is a constraint to study the behavior of this kind of materials, having particles diameters varying from centimetres to meters, since the size of a laboratory sample is related to the maximum particle diameter. For instance, in a triaxial test this relationship is approximately 1/6 to 1/5.

To overcome this fact, two main approaches have been used to estimate the rockfill strength properties, such as was discussed by Verdugo and De La Hoz [18]. The first approach is to use the technical literature by selecting conservative parameters and applying safety factors related to the lack of information. The second approach is to use testing methodologies such as homothetic curves, where the grain size distribution of the material is reduced to a smaller equivalent. Other methods include simple reduction of the maximum particle size in the sample.

In general, rockfill material have high values of hydraulic conductivity and a compacity level from medium to high, therefore their main behavior is drained. Its strength is composed at least by two components, the friction between particles and the energy necessary for the relocation of them. Other component that controls the behavior is the confinement pressure, where at low effective normal stress material shows dilatant behavior while at high pressure significant crushing at the contact points with reduced dilation is observed [19]. This have an effect on the peak of the friction angle as can be observed in Fig. 7.

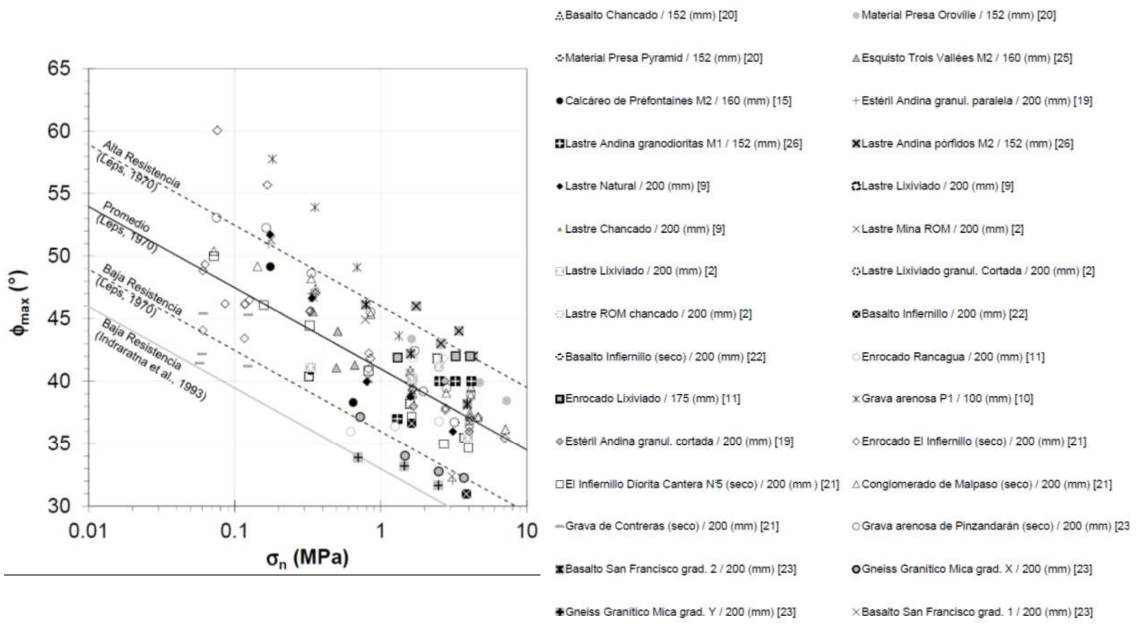

Fig. 7 – Drained Triaxial Test on Coarse Granular Soils and Rockfill [20]

Ovalle et al. [20] summarized a classical data base on rockfill test and boundaries proposed by Leps [21] and Indraratna et al.[22] and added data of coarse granular soils and rockfill from mining waste. It is possible to observe the reduction on the friction angle with the increase of normal stress, and a good fit of new data around the average boundary proposed by Leps. Also, it can be observed that values of confinement higher than 1 MPa show a reduction of data deviation, which could be effect of particle breakage that occurs due to high confinement pressures.

Particle breakage analysis from a size effect approach was developed by Ovalle et al [23], who carried out large triaxial tests on two different rockfill materials. Each material was tested carrying out two set of tests, for two Particle Size Distribution (PSD), on a large triaxial equipment using homothetic curves (factor of 4) with a maximum diameter of 160 mm and 40 mm. The results indicate that the coarser sample presents an increase in the amount of particle breakage and a slight decrease in the shear strength envelope compared with the smaller sample.

This finding is relevant for design and it must be taking into account, in particular due to the fact that the materials found in the field, used on dams construction, may have larger particle size than that allowed to be tested by laboratory equipment. Thus, the effect of size must be considered in order to not overestimate the strength of the material. In case that the technical literature is used for design, it must be kept in mind that data had the same constraints about the laboratory equipment restriction regarding maximum particle size.

On other hand, Dano et al. [24] developed an extensive review of the behavior of granular materials that were affected by particle breakage, and concludes that crushable soils are subjected to two dissipative processes when they are subjected to compression or shearing, these are friction and the energy consumed to create new surfaces and fragments (breakage). Both mechanisms produce a material more compressible due to the rearrangement of the fragments and consequently experiments a decrease on its shear strength. Also, it is mentioned than humidity contributed to the propagation of cracks and particle breakage, and this can derivate in settlements for dams or other structures.

2.2. Drainage System

A drainage system is one of the key components of a tailings dam to ensure its physical stability. However, it must be taken into consideration that many (or most) systems are built using sand or earthfill materials, which may not be able to drain sufficiently fast enough to ensure a low water table, due to their low saturated hydraulic conductivity.

Current Chilean regulations demand that construction of all tailings dams must include a drainage system in its design [25]. This decision is backed up by the good performance that drainage systems designed properly have shown in maintaining the water table levels below those required by design [26], and also because an improperly designed or missing drainage system has been identified as one of the main issues in the historical Chilean dam failures [3].

The design of the drainage system for tailings dam usually considers a basal drain located at or near the gully of the valley, at the point of lowest elevation, fed by smaller secondary drains that conduct the water from the abutments to the basal drain. The basal drain is considered the most critical in the dam, the common practice being to estimate its hydraulic capacity using safety factors equal or larger than 10 ($FS \geq 10$) for the operational case and equal or larger than 5 ($FS \geq 5$) for the hydraulic capacity required for Probable Maximum Flood (PMF) events. Secondary drains may be designed using smaller safety factors for operational and PMF cases, depending on their criticality and redundancy.

The main components of a drain include the granular material used for drainage, the steel pipes that serve as an additional drainage measure as a redundancy element (not considered in the safety factor estimation), and the system of one or more granular filters and/or geotextiles that protects the drain from eroded fine soil coming from the dam or its foundation, transported by seepage. In Fig. 8a an example of a typical basal drain cross section is presented using geotextile at the base of the foundation and granular filters between the dam sand and the basal drain. Geotextiles used as filters have been questioned lately in the design of the basal drain, because of issues related to its durability over long periods of time, as the basal drain must be keep working for many years after closure of the dam. On the other hand, properly designed envelope granular filters are expected to perdure far longer than the operation and closure period of the dam, as seen in Fig. 8b.

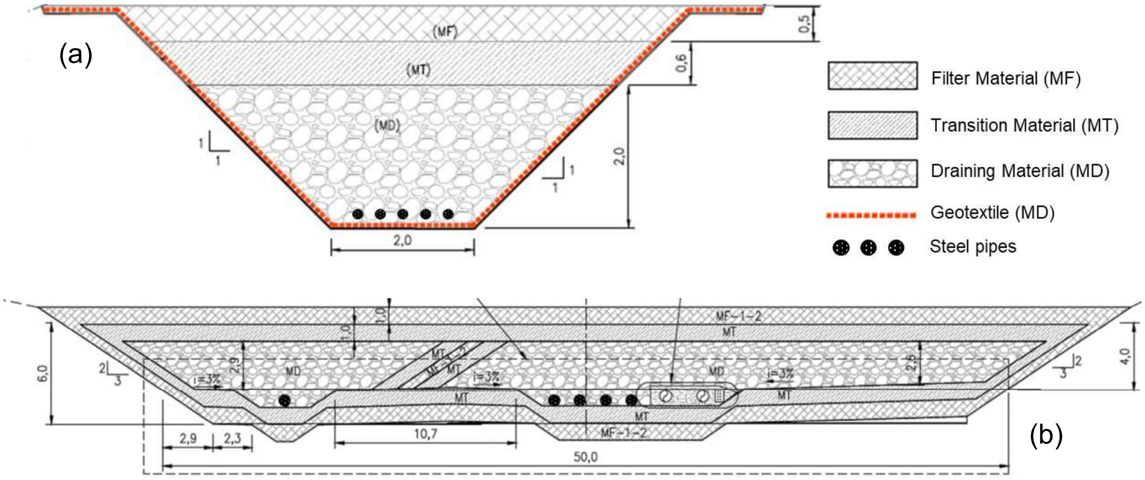

Fig. 8 – Cross section of a typical tailings dam drain (a) Drain with a geotextile as a filter for the foundation (B) Drain with an envelope filter solution.

Geosynthetics and pipes are usually not accounted in the design of the long-term physical stability of large tailings dams, due to their incapacity to withstand the adverse conditions (seepage of acidic fluids and large confining pressures) in the long-term. While it is expected that all large tailings dams designed by current standards have this factor in consideration, it is important that expansion projects revaluate the originally built drains carrying capacity and clogging by erosion resilience, without accounting for the contribution of these components and taking corrective measures in case the built drains fails to maintain the water table below the required levels.

Granular drain filters designed using state of the art in filter criteria [27] [28] should be used in the design of the drainage system. Special attention should be paid to the filter particles resistance, as filters must be build using durable, hard particles, to ensure that the material will not change its gradation significantly due to compressing and shearing stresses, considering that filter materials are usually located at the base of the dam, where the highest stresses are to be expected [27].

Due to the uniform materials used in the construction of the drains, having coarse particle size distributions (PSDs), and the steep valleys found in the Andes mountain range in which Chilean TSFs are usually located, the seepage through the drain does not follow the Darcy's law. Turbulent flow through materials with large voids is characterize using the equation developed by Leps [29], based on Wilkins equation [29]:

$$Vv = W\sqrt{m}\, i\ 0.54 \tag{1}$$

Where,

Vv: Water velocity in the material voids.

W: Empiric constant, which is a function of the material particles shape and the D_{50} of the PSD.

m: Hydraulic radius, function of the D_{50} of the PSD.

i: Hydraulic gradient.

For the Leps equation to be viable, a) the material must be constituted by large size particles, rounded or angular, mostly uniform, that do not generate any kind of cohesion, and b) there must be free flow (hydraulic gradients equal or lesser than 1). By evaluating the grain size curves of ten rockfill dams and their performance, and considering the effects of segregation, Leps recommended that the D_{50} may be considered the dominant size for flow calculations, provided that the minus 1'' (25.4 mm) material is less than 30% of the total material, by weight. In the case of well graded rockfill drains, the Canadian Centre for Mineral and Energy Technology (CANMET), through their Rock drain research program (1992-97), found that, in similar manner to laminar flow seepage through soils, characterized by Darcy's law, it's the D_{10} particle size that governs flow calculations when the rockfill material is well graded [30].

To successfully assess the high confining stress impact on the drainage system design in engineering phases, it is recommended to perform large scale oedometric tests by using samples with PSDs and mineralogy representative of the drain material to be used. It is important to allow the vertical deformation to stabilize before increasing the load, due to the creep expected in rockfill material because of stress redistribution in the particles. Additionally, measures of saturated hydraulic conductivity for each vertical load and PSDs before and after the execution of oedometric tests should be performed.

Commonly, drain materials largest particles are much bigger than what may be tested on laboratory, even for triaxial cells of large dimensions. A successful approach to circumvent this issue is the one proposed by Pollak & Bard [31], whom estimated the impacts of large confining pressures on ROM (‘Run of Mine’) and leached waste rock, with a D_{50} equal to 460 mm (18’’) and 120 mm (4,7’’), respectively, by testing samples with homothetic PSDs, with a maximum particle size of 200 mm (8’’) and a D_{50} equal to 73 mm (3’’) for the ROM representative sample and 35 mm (1,4’’), for the leached waste rock. The samples were tested under vertical stresses equal to 4, 8 and 12 MPa. The PSDs of the samples before and after the oedometric test, for each applied vertical stress, can be seen in Fig. 9a.

By considering that the D_{50} governs the hydraulic flow calculations, Pollak & Bard analyzed the D_{50i}/D_{50f} ratio evolution with increasing vertical stress, defined as the ratio between the D_{50} before (D_{50i}) and after (D_{50f}) the oedometer test execution, as shown in Fig. 9b.

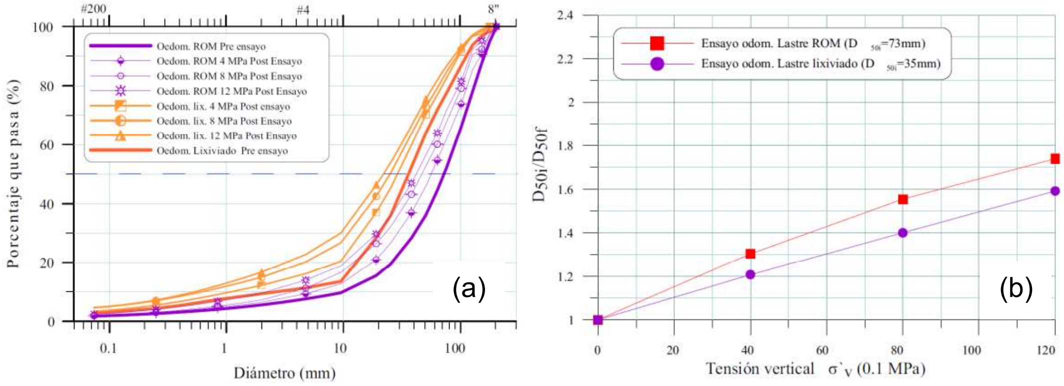

Fig. 9 – (a) PSDs of ROM and Leached waste rock sample, before and after the execution of Oedometric Tests. (b) Variation of the D50i/D50f as function of vertical stress modified from Pollak & Bard [31].

The variation measured in the original PSDs D_{50i}/D_{50f} ratio due to particle breakage, was extrapolated using Frossard’s results, who concluded that for two PSDs with different characteristic diameters but similar PSDs shape and mineralogy, the particle breakage resistance is proportional to the inverse of the square root of both characteristic diameters PSDs:

$$\sigma'_v \sim \frac{1}{\sqrt{D_{50}}} \tag{2}$$

Where,

σ'_v: effective vertical stress [kPa]

D_{50}: Diameter for 50% of material passing by weight [mm]

Equation (2) was first validated using the results of both samples tested, as seen in Fig. 10a, showing a good agreement between the laboratory tests results and Frossard's equation. Later, D_{50i}/D_{50f} ratios were estimated for both material based on the results of the samples tested, as it is seen in Fig. 10b. A reduction in D_{50} equal to 65 mm from 120 mm was estimated for the leached waste material, while a reduction in the D_{50} equal to 200 mm was estimated for the ROM material.

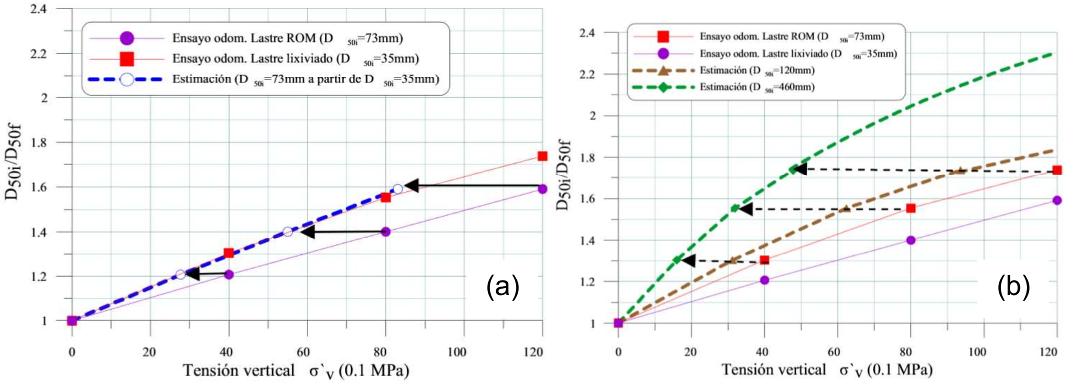

Fig. 10 – Estimation of degree of particle breakage at D_{50} (a) Verification using tested data (b) Extrapolation to original size PSDs [31]

Bard et al. [32] analyzed the results of oedometric tests performed on waste rock and riverbed materials, in samples with homothetic PSDs of 0.95 m diameter and 1 m height, and a maximum effective vertical stress σ'$_v$ equal to 4, 8 and 12 MPa. The summary of their results is shown on Fig. 11, with both porosity and void ratio in the y-axis, additionally, data of large granular material found in the literature is also included [3][32]. The authors found that an uniform coarse waste rock material showed an over-consolidated behavior for vertical stresses below 0.9 – 1.0 MPa, while a behavior similar to a normally consolidated soil is seen for higher vertical stresses, with a significant increase in the compressibility of the material, attributed to particle breakage induced by high-stress. On the other hand, the riverbed material showed an over-consolidated behavior within the whole range of applied vertical stresses (up to 2.4 MPa). It may be assumed that the particle breakage in the material is not significant as to alter its oedometric behavior, in the range of vertical stresses which was tested.

The high confining stresses associated to tall tailings dams have a direct impact on the final porosity of the drain material and on its particle size distribution, two key components in the drain hydraulic capacity, due to high-stress induced particle breakage and its related increase in compressibility of the material, as shown by the results presented above. When designing the drainage system for a tailings dam, is important to assess whether the materials used as drains will experiment significant particle breakage by laboratory testing of samples with representative PSDs. The design of the drainage system must be tuned to include the effect of particle breakage in case that the expected vertical stresses be higher than the threshold stress for significant particle breakage to occur.

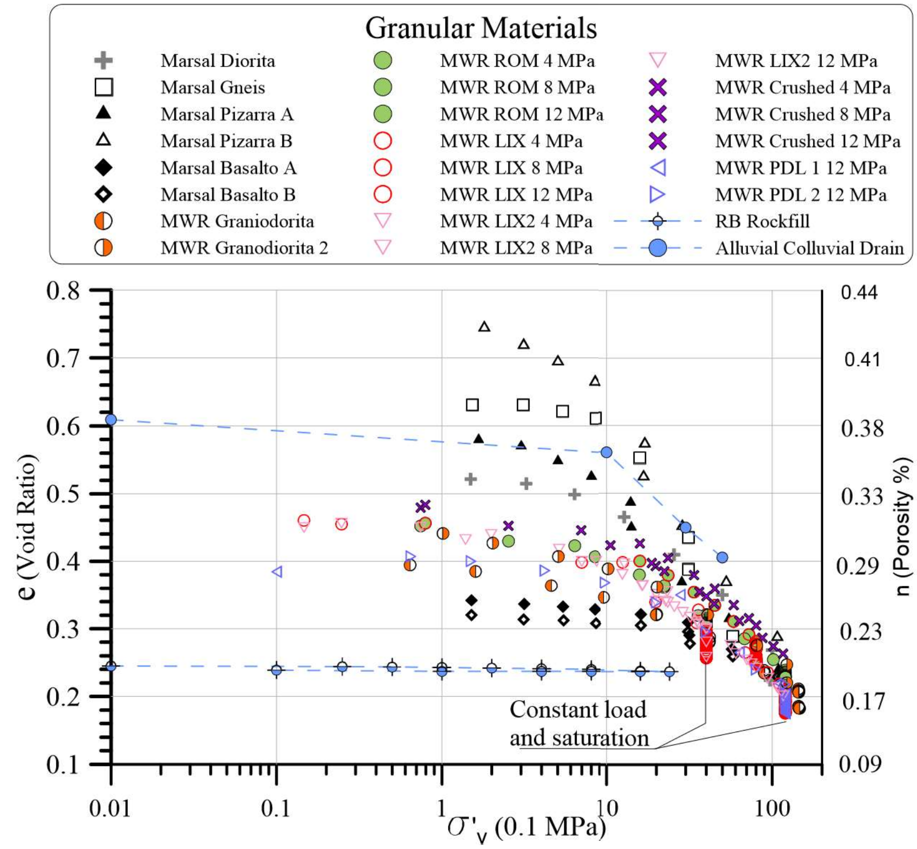

Fig. 11 – Oedometric compressibility of mine waste rock material and gravels ([3] modified from [31])

2.3. Soil Foundation

Subsurface exploration is fundamental for identification and characterization of the foundation materials, because of that, the quality and quantity of boreholes and in-situ tests have been discussed by several authors. For instance, Briaud [33] carried out a simplified calculation on the number of borings and triaxial tests required to predict a soil property with a 98% of confidence level within an area of 40m by 40m (8 stories building). His results indicated that it would be necessary to carry out 640 triaxial tests (considering 20 triaxial tests per boring with a depth of 40 m) and 32 borings to reach such level of confidence. It ought to be noted, however, that in engineering practice for such kind of structure and its related area only 4 or 5 borings are usually carried out [33].

If the magnitude of the tailings dams and related impoundment area are considered, by using the same methodology as Briaud [33] the number of tests will grow by orders of magnitude; for example Talabre tailings dam, one of the largest deposit in terms of area in the world, which spans an area of more than 50 km^2 with a dam of 21 km long. If the same exercise is carried out, more than one million of boreholes would be required. Consequently, it is easily seen the exploration by boreholes and samples testing would never be enough.

Once this limitation is known, the aim must be to reduce the lack of information by integrating geology and geomorphology aspects, indirect (geophysics) and direct (boreholes) explorations, in-situ and laboratory testing, and to assure a continuous update following every new growth of the tailings dam. This is specially needed when the stage of growth is larger in height than the original design height.

Therefore, it is challenging to correctly estimate the soil foundation properties in any structure, and particularly, in a tailings dam due to its dimensions and location. Many of them are located in narrow valleys where the basin is composed of alternated geological-geotechnical units, usually of fluvial, alluvial and colluvial origin, with different degrees of compressibility, hydraulic conductivity and shear strength parameters. Additionally, it is essential to identify geotechnical units that may become saturated and subjected to a gradual increase of the static loads produced by deposit growth, which may induce a contractive behavior on the foundation soil, reducing drastically their shear strength under undrained conditions (flow failure).

There are records of failures whose failure mechanism defined has been the soil foundation, caused by raising of dams in height beyond its initial design, deficient subsurface characterization (geological and geotechnical model) and an inadequate design of construction stages. Azam and Li [34] collected data of tailings dam failures until 2009 and classified each one in eight categories, as it is shown in Fig. 12.

It is observed that foundation failure has a greater distribution (7% of cases) than slope instability and overtopping. Additionally, it is well known that in the last ten years, two of the most studied tailings dam failures focus on soil foundation as the failure mechanism. These are Mount Polley (2014) and Cadia (2018), both of which have been analyzed by experts and have their Panel Expert Reports published ([14] and [15]).

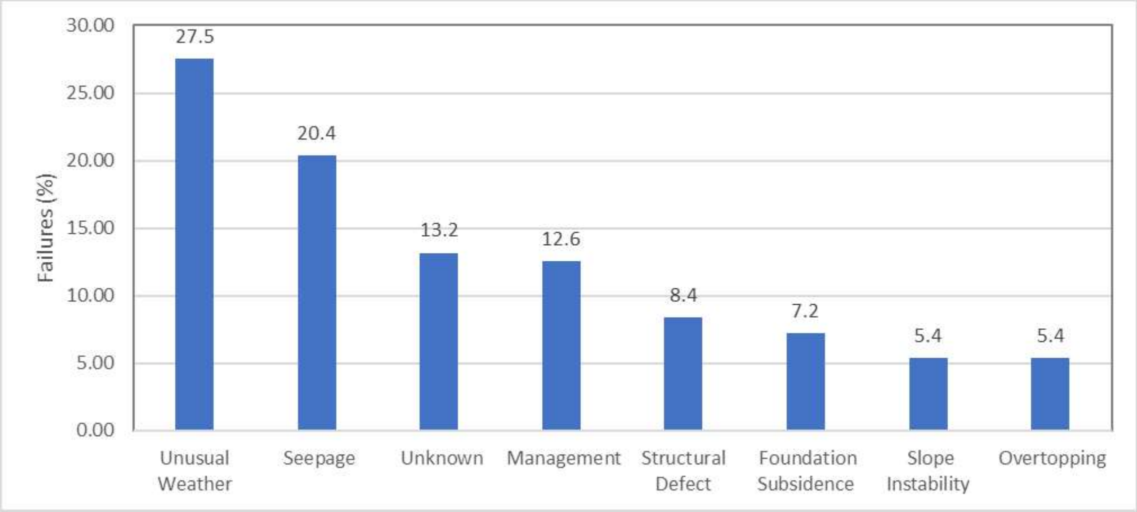

Fig. 12 - Tailings Dams Failure (Modified from [34])

According to Mount Polley Panel Review [14], there are three reasons why a foundation can be weak having the potential to fail, which are a) the presence of an undetected weak layer, b) the presence of a brittle layer that loses strength under loading and which can develop a smaller resistance than the load applied by the dam or embankment, and finally, c) the presence of a compressible stratum that when is loaded by construction, reaches a threshold stress condition, developing high pore pressure that produces a weakening of the material by development of its undrained behavior. Moreover, the liquefaction phenomenon for loose and saturated sands can be added to the factors above.

To illustrate the main challenges related to high tailings dams, each one will be exemplified with the findings identified by experts in Mount Polley and Cadia reports. Fig. 13 and Fig. 14 show the section of analysis on the breach for each failure, identifying the soils foundation materials.

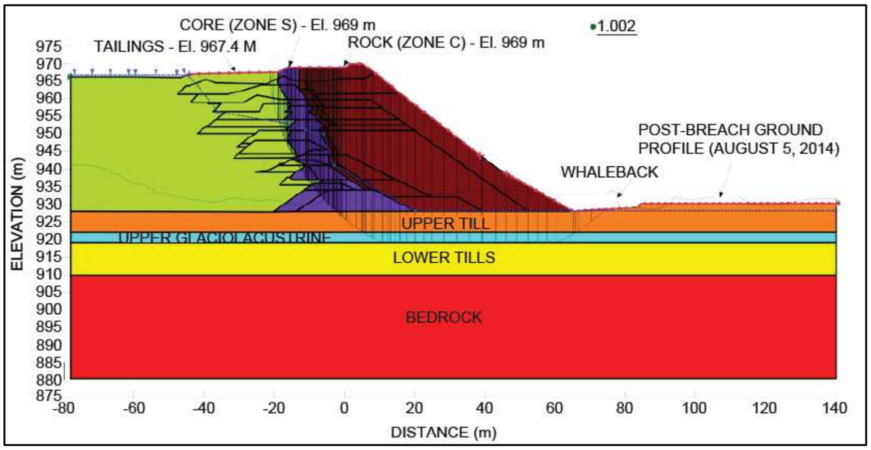

Fig. 13 - Limit Equilibrium Analysis – Mount Polley Breach Section [14]

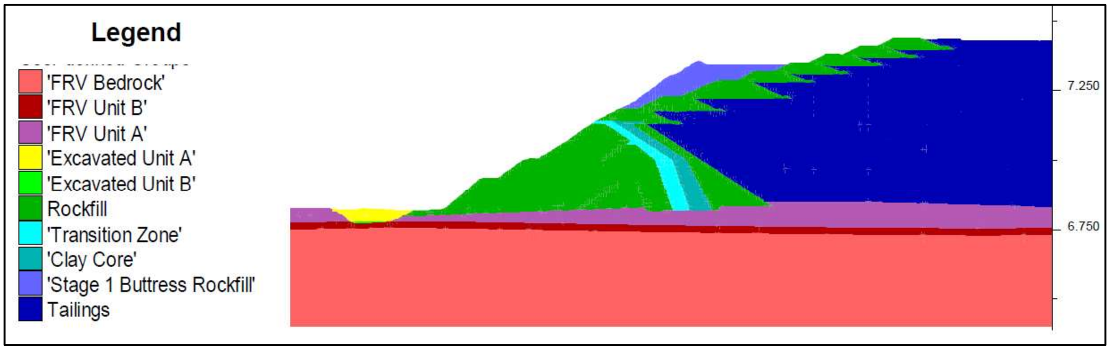

Fig. 14 - Deformation Analysis – Cadia Breach Section [15]

Soil Foundation Characterization

It is fundamental to know the geological background by a complete subsurface investigation (boreholes, field tests and samples collection) and geotechnical characterization (in situ and laboratory tests). This affords identification of all the materials which compose the foundation and selection of an accurate set of resistance and deformation parameters, which will be used in the stability and deformation analysis.

The cause of Mount Polley failure was the inadequate identification of geotechnical properties and geological history of a Glaciolacustrine Layer (also called Upper GLU), in particular, the loading conditions of previous sub-glacial and pre-glacial geological environments. These geological conditions produced an overconsolidated state on the layer, which was neglected in the design stage since the change to a contractive behavior when the soil reaches its normally consolidated state [14] was not considered.

On the other hand, Cadia failure was developed by the FRV Unit A, a layer extremely weathered and composed by volcanic sources and residual soils. This stratum after failure was characterized as a lower density layer with a significant higher void ratio, highly compressible and strain-weakening behavior when subjected to loading (loses strength with deformation) [15].

Dam construction design

A construction plan which includes the potential behavior changes of the different soil foundation layers due to the increase in the confinement pressures for the continuous dam growth is essential. Changes in loading and unloading affect the stress path of these materials. The soil foundation strength and also dam materials properties (for static or seismic conditions) may be overestimated if these changes are not considered.

In the case of Mount Polley, the extra loading related to the dam growth exceeded the preconsolidation pressure, inducing a normally consolidated state on the Upper GLU layer, causing a contractive response in the material. Thus, the layer developed positive pore pressure and the behavior changed to undrained, which exhibits less resistance than the drained behavior used for the stability analysis which validated the design [14].

While in Cadia's case, the failure report [15] indicates that accumulated deformations were recorded on the foundation during the last months of the last construction stage (stage 10), that phreatic level on the breach zone was close to its highest magnitude, and that an excavation was located at the toe of the dam breach, all these factors contributing to destabilization of the structure. It is important to mention that two buttresses were designed for growth stage 10, but only one of them was constructed before the failure date. This event triggered the posterior failure mechanism related to tailings liquefaction and the breach generation [15].

3. CONCLUSIONS

The main conclusions or current challenges that must be considered on the tailings dam design are:

- The main challenge in a high tailings dam, composed by sand, is to carry out a correct in-situ characterization, since the material generally changes along the construction stages and the lifetime of the dam, due to variations of ore mineralogy, segregation, compaction, particle breakage, and effects related to operation and construction phases. In this context, an in-situ characterization program is fundamental to check, validate, and carry out new stability analyses of the dam and the impoundment. Currently, the practice recommends performing the laboratory testing of in-situ extracted specimens and field test as CPT, in order to use these results and Critical State methodology proposed by Been and Jefferies [11].

- Particle breakage phenomena at high level stresses and its effects on the material shear strength and hydraulic properties of rockfill and coarse granular materials must be considered to properly characterize their strength and hydraulic properties, which are fundamental for the stability analysis of the dam and the integrity and functionality of the drainage system.

- The existing limitations of rockfill testing equipment and the lack of data about natural samples tested (original PSD) must be considered for design. Mostly, the data available correspond to a modified material, whose PSD was reduced by homothetic curves or its larger diameters particles were cut to be able to test on the existing equipment. Therefore, according to Ovalle et al. [23] for larger particles the size effect on particle breakage is a reduction of their strength envelope in relationship with smaller samples. Because that smaller samples are tested and used as data the strength properties of rockfill can be overestimated.

- Take into consideration particle breakage in the design throughout all dam projected stages, which means that the PSD of the materials must be viewed as a dynamic variable that may change in each new construction phase (new loading conditions). Also, is important to analyze the behavior at the closure condition and to incorporate other effects as aging, erosion by environmental factors, and others than could affect the strength properties of the material.

- Development of an exhaustive subsurface investigation (direct and indirect methods) in combination with a comprehensive study of its geological framework is fundamental for identifying all units presents on foundation and for defining their hydromechanical behavior, in order to evaluate stability of a tailings dam.

- Assessing the material behavior in each new construction stage is necessary, due to the fact that the original design may have changed, and thus, new loading conditions or different stress path can produce effects not considered at the first design stage related to changes on the material behavior.

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