

High sand tailings dams: main challenges

Presas de relaves de arena de gran altura: desafíos principales

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The design and construction of higher tailings dams result in much higher confining pressures which can affect the geotechnical behaviour of tailings sand dams. This becomes even more relevant in regions with regular seismic activity. This article presents results and analyses of oedometric compressibility as well as cyclic resistance of tailings at high confinement pressures. Moreover, results of crushing and compressibility of gravel and rock-fill at high confinement pressures are also studied, since they form part of the drainage system of tailings dams. The seismic stability and deformation of tailings dams is discussed from the numerical analysis point of view. The importance of the selected PGA value and how has evolved in time in the Chilean engineering is shown. Finally, aspects related to the observational method to be applied during the construction and operation of tailings dams, are described. Future trends on mine waste disposal are introduced such as thickened and paste tailings and filtered tailings.

Keywords: tailings sand dams, high confining pressures, cyclic resistance, observational method, mine waste disposal

El diseño y construcción de presas de relaves más altas resulta en presiones de confinamiento mucho mayores, lo cual afecta el comportamiento geotécnico de presas de relave de arena. Esto llega a ser aún más relevante en regiones con una actividad sísmica constante. Este artículo presenta resultados y análisis de ensayos de compresibilidad edométricos así como de resistencia cíclica de relaves a altas presiones de confinamiento. Además, se estudian resultados de rotura y compresibilidad de gravas y enrocados a altas presiones de confinamiento, ya que ellos forman parte del sistema de drenaje de las presas de relaves. Se discute la estabilidad sísmica y deformación de presas de relaves desde el punto de vista de análisis numérico. Se muestra la importancia del valor de PGA seleccionado y como ha variado en el tiempo en la ingeniería chilena. Finalmente, se describen aspectos relacionados con el método observacional a ser aplicado durante la construcción y operación de presas de relave. Se incluyen tendencias futuras sobre disposición de residuos mineros tales como relaves espesados, pastas de relaves y relaves filtrados.

Palabras clave: presas de relave de arena, presiones de confinamiento elevado, resistencia cíclica, método observacional, depósito de residuo minero

Introduction

The design, construction and operation of tailings sand dams represent an important geotechnical task in terms of stability, especially under foreseen strong seismic events. Valenzuela (2016) analyses the effect of fines content and permeability on the seismic performance of tailings sand dams in Chile. He also pointed out the fact of the significant growth of the mining production, which has led to the necessity of large tailings deposits, many of them resulting in dams with increasing height. Consequently, the study of the geotechnical behaviour of granular materials under high confining pressures becomes necessary. This article

extends the contents of permeability, drained and undrained resistance of sands under high pressures previously studied by Valenzuela (2016). The attention here is focused initially on the compressibility and cyclic resistance of tailings under high confinement pressures. Then, crushing and deformation of gravel and rock-fill materials under high confinement pressures are studied because they form part of the drainage system of tailing dams. The use of numerical analysis in the study of the stability of tailings dams is subsequently introduced. Furthermore, the observational method is considered as an important tool of assessment of tailings dams performance. Finally, new trends of mine

waste disposal are mentioned to tackle challenges of space and efficient use of water.

Deformation of sands at high confinement pressures

Oedometric compressibility in sands is very low, independent of the initial void ratio for confining pressures lower than 1 MPa. Oedometric compressibility of these materials begins to increase as particles break up, when compressibility of the granular skeleton becomes independent of the initial arrangement. Figure 1 shows the results of oedometric compressibility of tailings sands samples S1 to S5 with uniformity coefficient C_u (d_{60}/d_{10}) between 1.0 and 3.2, of natural Ottawa quartz sands samples (Murthy *et al.*, 2007), of rounded particles and with C_u between 1.5 and 2.7, and of Hostun sand (Colliat-D'Angus, 1986), of angular particles and with C_u of 1.7.

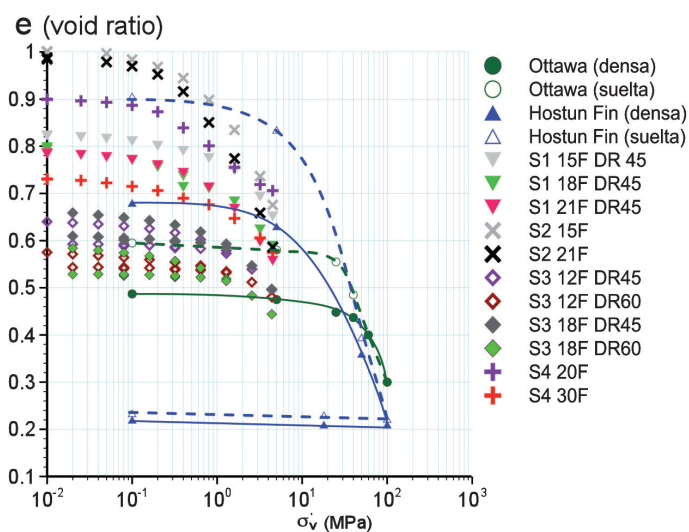


Figure 1: Oedometric compressibility of quartz, Ottawa, and Hostun tailings sands (adapted from Bard *et al.*, 2014).

Figure 1 shows that rounded Ottawa sand particles undergo a sudden change in compressibility due to the break-up of particles when they are subjected to effective vertical stresses $\sigma'_v > 30$ MPa. In Hostun sand, however, the increase in compressibility is progressive, due first to loss of particle angularity and then to the gradual break-up of particles. For $\sigma'_v > 40$ MPa, both types of sands exhibit a similar degree of compressibility.

Tailings sands in general exhibit low compressibility up to $\sigma'_v = 1$ MPa, provided they have a void ratio of at least 0.8 approximately, evidenced by a moderate volumetric change

similar to the one observed in the sands discussed above. At pressures of $\sigma'_v > 1$ MPa, compressibility begins to increase progressively, due to breaking of the more angular edges of tailings sand particles. This behaviour in the $e - \log \sigma'_v$ plane is very similar to that of fine Hostun sand, a fact that could indicate a way to predict the possible behaviour of tailings sands at vertical stresses above 4 MPa, the maximum pressure used in the tests with samples S1 to S5.

Cyclic resistance of sand at high confinement pressures

Figure 2 shows the cyclic resistance ratio CSR obtained for 100% of pore pressure generation ($\Delta u = \Delta \sigma'_o$, initial effective pressure) by means of cyclic triaxial tests at high confinement pressures and for different contents of fines. At low confinement pressures, results are similar to those reported previously for Verdugo (1983), in which CSR is clearly reduced when FC increases. However, for pressures above 1 MPa and below 3 MPa, impact of the percentage of fines, for the range of tested samples, practically disappears.

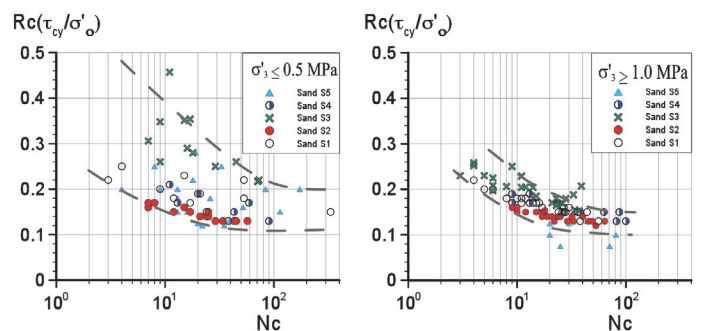
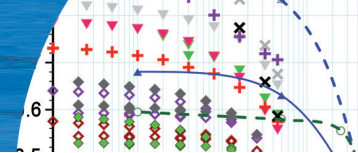


Figure 2: Cyclic resistance RC of tailings sands as a function of the number of cycles and of confinement pressure, for different FC, 15%-30% (Bard *et al.*, 2014)

Deformation of gravel and rock-fill at high confinement pressures

The behaviour of gravel and rock-fill subjected to high confinement pressures is of great importance because these materials are used in the construction of the basal drains in tailings sand dams. Modification of their grain size distribution during break-up of particles and formation of fines could reduce estimated permeability significantly compared to permeability at the original particle size. Bard *et al.* (2015) analyse the behaviour of these materials in drained, monotonic triaxial tests using samples of 1 m diameter and 1.8 m height, subjected to pressures of up to 3 MPa, in copper mine waste rock (Bard *et al.*, 2007, 2012;



Valenzuela, 2004; Valenzuela *et al.*, 2008) and coarse river bed material samples used in the construction of gravel dams. The results referring to variations in their grain size distribution are shown in Figure 3.

The waste rock MWR and river gravel RB were also subjected to oedometric tests in samples of 0.95 m diameter and 1 m height, and maximum confinement pressures of $\sigma_v = 4.8$ and 12 MPa. Results of these tests are shown in Figure 4, together with results reported in other studies (Marsal and Resendiz, 1975; Marsal, 1977).

The conclusions of the referred studies are as follows: i) natural gravel of polyimitic origin and relatively well-graded particle sizes ($1 > C_u > 3$), such as the RB sample, does not exhibit particle break-up up to pressures of $\sigma'_v = 2.4$ MPa to which the sample was subjected; ii) the rock-fill material coming from quarries exploited by blasting exhibits a pre-consolidated behaviour, with low compressibility, up to pressures of the order of $\sigma'_v = 0.9$ MPa, and then a significant increase in compressibility due to particle break-up. It can be observed that the void ratio varies proportionally to the logarithm of imposed vertical stresses, similar to a normally consolidated behaviour. This aspect is similar to that observed by several other investigators of granular soil behaviour.

Considerations on stability and deformations of tailings dams

For the purposes of this paper, the discussion of stability analysis of very tall dams is limited to slope stability and deformation analysis, for both static and seismic conditions. The analysis assumes that the foundation is sufficiently resistant and sufficiently dense to prevent material impacts on dam stability and deformations of the dam due to foundation conditions.

Limit Equilibrium Methods LEM

The most widely used methods of slope stability analysis for static loads and post-earthquake conditions are limit equilibrium methods LEM. In general practice, a safety factor $FS \geq 1.5$ is considered acceptable for static loads on potentially sliding surfaces that could affect overall stability of the dam or increase the risk of emptying the impoundment. It is common to accept a $FS \geq 1.0$ for post-

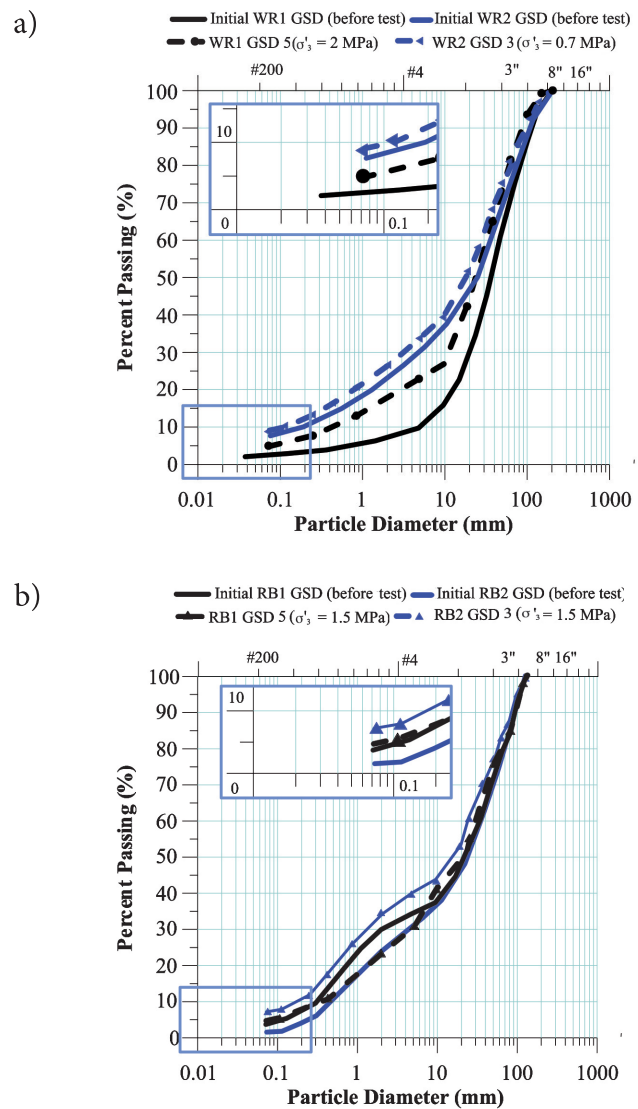


Figure 3: Particle sizes, before and after triaxial testing; a) mine waste rock and b) river gravel (Bard *et al.*, 2015)

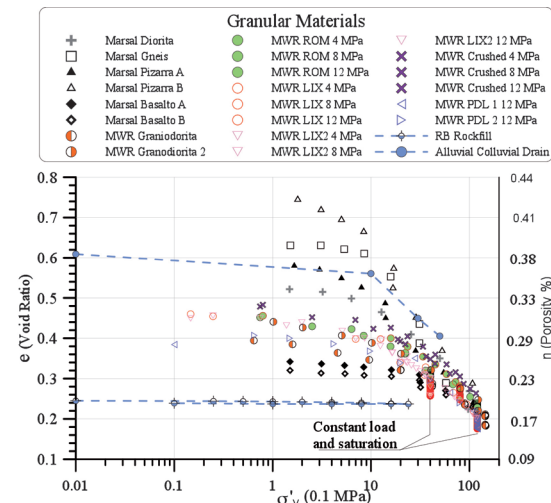


Figure 4: Oedometric compressibility of mine waste rock and gravel (Bard *et al.*, 2015)

earthquake conditions. Static analysis of downstream and centerline dams considers drained resistance of sands, assuming in practice a conservatively high phreatic level in the body of the dam. Post-earthquake analysis considers that sands located below the assumed phreatic level or saturation line have mobilized positive pore pressures and reached liquefaction. The ultimate undrained resistance value σ_u , as obtained in tests conducted on large deformations approaching steady-state or perfect plasticity conditions, is also considered conservatively for all sands located below the assumed phreatic line.

Even in cases not subjected to seismic stresses, undrained behaviour could be induced under special conditions; for example, if the dam is increased in height too rapidly to permit rapid dissipation of pore pressures. For large dams, this risk is mitigated by the hydraulic deposition of sands on the slopes by sectors, allowing time for proper drainage before proceeding to compaction. Another example of non-seismic event is the case of a large and sudden deformation of the foundation.

The validity of LEM applied to seismic analysis of tailings dams in the form of pseudo-static analyses has been questioned for decades, because of both the uncertain meaning of the FS obtained, and the choice of the pseudo-static seismic coefficients k_h/g or k_v/g themselves, which are used to determine the inertial forces that hypothetically represent the earthquake action. When this type of pseudo-static analysis is conducted, the regulatory agency in Chile for example MM (2007) requires a value of $FS \geq 1.2$. Nevertheless, in the case of major dams, either because of their height or because of the potential risk, a pseudo-static analysis may only be considered as an indicator.

Seed (1979) indicates that the pseudo-static method cannot be used when the loss of resistance of materials is above 15%. There is evidence suggesting that stability conditions of dams, analyzed using pseudo-static methods may be over-valued. The opposite case is also true, as some dams have performed adequately when submitted to high seismic accelerations.

The definition of seismic coefficients based on local experience has been reviewed every time large magnitude earthquakes have occurred. Experience in Chile shows that from the 1950s to the 1970s, seismic coefficients k_h used in the practice have

varied typically between 0.12 and 0.15. However, deeper knowledge of the country's seismology, as well as the pressure represented by the seismic risks associated with increasingly taller dams, have increased the values of k_h to a typical range of 0.15 to 0.18. Since the end of the 1960s, a large number of global studies and investigations have attempted to rationalize the selection of the seismic coefficient, which is generally required to refer to an acceptable deformation level. However, in most cases the final values or expressions have referred only to the maximum ground acceleration or PGA (Bray and Travasarou, 2011; Duncan *et al.*, 2014). The growing PGA values selected for design earthquakes shown in Figure 5 for Chilean projects makes applying these relationships to PGA questionable for earth dams, and especially for very tall dams.

In the cases shown in Figure 5, the value of PGA, and consequently the value of k_h , was increased almost four times the original value for the same project, which does not seem reasonable, since PGA occurs only for an extremely brief moment. It should therefore not be used as the only representative element of the earthquake, and even less so of the dynamic response of a structure like a sand dam, generally being more flexible with increasing heights.

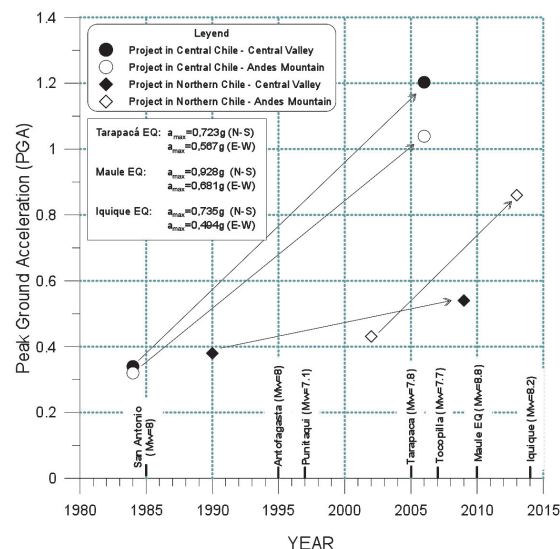
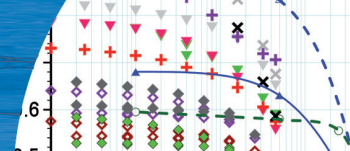


Figure 5: Example of design PGA value variations for the same site in the course of several years. Also included are the most relevant earthquakes recorded in Chile in the past 30 years.

The response of a dam to an earthquake depends not only on the type of soil and height of the dam, but also on the frequency and duration of the earthquake, on the dam's own resonance period, the dam's slopes and on its dynamic



characteristics, such as damping and shear modulus. Replacing all of these factors with a single factor or PGA is therefore an over-simplified approach.

Designers and researchers increasingly agree that use of LEM for seismic analysis of tailings dams is only justified for initial verifications or for small dams that do not represent high risk, provided that the analysis is complemented with an estimate of remnant deformations.

Simplified analyses to estimate seismic deformations

The simplified method of estimating deformations produced in a dam by an earthquake was first proposed by Newmark (1965), who compared the potentially sliding mass to the model of a block moving on a sloping plane. Applying the same model, Hynes-Griffin and Franklin (1984) estimated the accumulated deformation of the block using 348 records of horizontal earthquakes and 6 synthetic records. Similar procedures were used by Makdisi and Seed (1978), Sarma (1975), and Ambraseys (1960), who proposed curves that make it possible to obtain the remnant deformation u based on the ratio k_y/k_m . A comparison of these last proposals was presented by Seed (1979), who observed a low dispersion of average values.

Recently, Bray and Travasarou (2007, 2009, 2011) presented a probabilistic method to estimate accumulated deformations of an earth dam subjected to seismic action. Based on this method, they proposed a procedure for defining a seismic coefficient based on the response of the particular structure under analysis as a function of the level of remaining deformations considered acceptable. The method additionally takes into account the seismic moment M_0^1 of the design earthquake, spectral acceleration S_a , and the characteristics of the dam (height H , shear wave velocity of the material V_s). The procedure is supported by analyses of 688 records of 41 different major earthquakes, using a non-linear coupled stick-slip model, which includes uncertainty or probability in the estimate of the seismic displacements.

This method, while considering characteristics inherent to the particular earthquake and to the dam, as well as the *a priori* definition of an acceptable level of deformation based on a

¹Seismic moment is used to quantify the energy released by an earthquake using the scale of moment magnitude M_w .

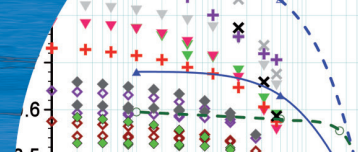
probabilistic criterion, could be used as an approximation for the analysis of deformations and stability of earth dams. However, the method requires a very elaborate analysis that is not justified, at least for dams of complex geometry and great height, since there are numerical methods that provide a more direct analysis of stability and deformations, as discussed below.

Numerical or “direct” methods of seismic analysis of dams

Numerical methods of analysis for stability, referred to as “Direct and Fundamental” according to ICOLD (1986), and discussed by Finn (1996), have become increasingly useful in recent decades, mainly for the analysis of dams of greater height or higher risk. These methods use numerical tools such as finite elements or finite differences. Descriptions of the methods, available software, and variations, have been discussed by Ozkan (1998), Finn (2000) and Marcuson *et al.* (2007).

One possibility for dynamic analysis of tailings dams involves a constitutive law based on a perfect elasto-plastic soil model with a failure criterion such as Mohr-Coulomb’s, an alternative frequently used in the analysis of tailings sand dams. This indicates that dynamic stresses that do not induce plastification of the material, do not induce dissipation of energy either. The dynamic equilibrium equations therefore include a Rayleigh-type damping, the value of which depends on the fundamental period of the dam. The shear resistance parameters of sands are obtained from triaxial tests, and the variation in rigidity can be deduced with hyperbolic data adjustment, as proposed by Duncan and Chang (1970), based on triaxial tests that cover the whole range of expected tensions in the dam. Properties of rigidity in the face of small deformations are obtained from special tests, such as resonating column, bender elements, or triaxial tests conducted on small deformations.

Although the perfect elasto-plastic constitutive model together with Mohr-Coulomb’s failure criteria do not permit relatively rigorous estimates of permanent shear and volumetric deformations prior to plastification of the material (maximum resistance), this model is generally adopted because it is a relatively simple constitutive model, capable of being implemented with relative ease, and more importantly, with full awareness of the values used in model



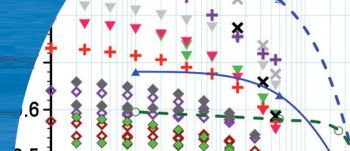
parameters and the model's limitations. In practice, the main reasons for using this model have been: a) more sophisticated models require more testing, which additionally require "unaltered" calibration samples, that frequently are not available during the design stages, when only a limited volume of samples from a pilot plant are obtainable; b) due to the dimensions attained by tall tailings dams, the range of confining pressures is quite wide, requiring the model to be capable of working within a wide range of pressures. This situation can be covered by the elastic-plastic model, using an appropriate variation of rigidity related to the confinement level; c) seismic stress induces complicated stress trajectories with stress-deformation responses not reproduced efficiently by alternative constitutive models; d) for the purpose of engineering design, use of a perfect elasto-plastic constitutive model and the Mohr-Coulomb failure criteria are sufficient to orient design, determine dynamic response of the structure, and evaluate deformations and safety, under static and seismic conditions.

One alternative for evaluating possible liquefaction of saturated sands and tailings is to assess the increase in pore pressures that will become manifest in the dam in a seismic event, using formulations proposed by Martin (1975) or Byrne (1991), which are calibrated using cyclic laboratory tests. These methods provide a good approximation but require an extensive set of laboratory test data within a wide range of stresses, calibration of which is not always feasible with a single equation governing the increase of in situ pore pressures. The tendency is, therefore, to prefer simpler but more conservative methods, such as evaluating stability on the assumption that the saturated zone below the assumed phreatic line develops 100% of the undrained resistance to large deformations, due either to cyclic mobility or to actual liquefaction.

There are some basic practical recommendations about the precautions to be taken in using numerical methods which are worth mentioning: i) adequate inclusion of Rayleigh's damping using the perfect elasto-plastic model; ii) appropriate selection of mesh dimensions, to permit transmission of the shear waves induced by the seismic event; iii) use of sufficiently wide dimensions in the model to keep borders from affecting dam response; iv) care in projecting the transfer of the seismic event defined at the surface (free field) to the basal rock under the dam wall;

v) verification that the model is capable of reproducing adequately the design acceleration spectrum in the free field; vi) verification that the level of deformation induced by the assumed earthquake is compatible with the level of rigidity and damping assigned to the sands; vii) adequate selection of the growth stages to be analyzed, given that the fundamental period of the dam varies in proportion to the increase in height; and viii) sound judgment in verifying the risk of topographic amplification and tri-dimensional effect due to the shape of the dam and topography of the project site zone.

Although numerical methods have improved greatly in recent times, they should not be used as the only design tool. Instead, they should be used to verify the seismic responses of the dam. This verification is becoming more and more necessary because maximum ground acceleration, duration, and frequency content of design earthquakes, even for the same location or site, have been increasing along with more complete knowledge of the seismicity and tectonics of the site under study, and moreover because of the trend to construct ever taller dams. In general, experience shows that, in many cases of downstream sand dams with healthy design criteria and preliminary stability verified by LEM and reasonable seismic coefficients, subsequent numerical direct methods only rarely have indicated conditions of global instability that could put good performance of the dam at risk. However, the numerical analysis has been important for identifying dam deformations in response to seismic stresses, eventually requiring adjustment of the crest to guarantee a minimum width and to provide the required design freeboard, especially in the closing stage. In very tall dams subjected to powerful earthquakes, these analyses can show deformations – generally in the direction of the slope – which may affect part of the dam crest, because one characteristic of non-cohesive soils such as low-FC sands is that potential slides would occur in an "infinite" slope. In such cases, the recommended course of action is to verify that such deformations, provoked by high magnitude earthquakes of low probability, do not affect more than 20 to 25% of the crest width. Although a common practice in many dams has been to accept minimum dam's crest width between 10 and 15 m, in the case of tall dams especially in seismic countries, the width of the unaffected portion of the crest should be no less than 15 to 30 m, depending on the



type of dam – downstream or centerline – and on the height of the dam and the risks visualized.

The methods discussed above estimate only deformations resulting from the change in effective stresses or in the stress deviator, and do not include deformations in non-cohesive granular soils due to the effect of vibrations (densification due to particles arrangements).

Swaigood (2003) and Bureau *et al.* (1985) have proposed curves to estimate total dam deformations, including those associated with changes in actual stress and those due to densification. These curves are based on the historical record of earth embankment and rockfill dams deformations during earthquakes of diverse magnitudes. Swaisgood bases his proposal on the reports of 69 documented cases, although none of them exceeded a $PGA > 0.7g$. Bureau *et al.* (1985) define the concept of the Earthquake Severity Index ESI, which depends on earthquake magnitude and PGA at the site of the dam emplacement. In the case of the definition of the free board for a sand dam, the above methods could be used as a reference for the verification of the total settlement of the dam but taking in consideration that both methods were based on the data provided by earth embankments and rockfill dams analysis. It is of great interest for the development of the engineering of tailings sand dams to register the settlement of sand dams after each earthquake, in order to build up a set of evidences of the actual settlements of this specific type of dam.

The observational method in the operation of tailings dams

Unlike dams built to store water, tailings dams are constructed over a period of several years along with the operation of the mine. This is especially the case with tailings sand dams, in which the main construction material for the dam is obtained by cycloning the tailings obtained from the mineral flotation process. It is common therefore for a tailings deposit, and consequently the construction and operation of the tailings dam, to take several years or decades. The long construction period inserted into an industrial operation presents opportunities and challenges for the optimal performance of these dams, not only from the geotechnical point of view and that of overall stability, but also for operational ease, safety, and cost. The opportunities arise precisely from the long operation period, which, if adequately

planned, permits application of the observational method (Peck, 1980; Morgenstern, 1996). The observational method requires suitable instrumentation and control schemes for the periodic and sometimes continuous monitoring of the most important variables, such as static and dynamic piezometric levels, volumes of seepage flow, quality of water in drains, deformations in key points of the dam, and response of the dam to accelerations during earthquakes of some magnitude. In addition, the results obtained from instrumentation and from quality controls must be interpreted and analyzed periodically by geotechnical specialists.

Table 1 lists the geotechnical instrumentation that has been installed in tailings dams in Chile. Unfortunately, although some of the readings are available through the controller agency, this is not the case for interpretative analyses of the registers. The information provided by instrumentation should be complemented during dam construction and operation, and on occasion during the post-operation period, by geotechnical characterization tests of tailings sands whenever changes occur, either in the mineralogy of the tailings and in the sands produced, or in the quality of fines contained in the sands. Testing, both in laboratory and in the field, should determine, for example, possible variations of permeability and resistance of the sands, but also variation of in situ densities of the sands at different depths. Control and monitoring systems must be in place to ensure the adequate performance of these dams, to verify periodically compliance with design hypotheses, and to allow the timely introduction of any necessary modifications for their adequate performance in the medium and long term (Morgenstern, 1996). For tailings dams, the long term includes construction and operational time, post-operational period, and eventual closure within an undefined time horizon.

It is critical that the observational method relies on the participation of geotechnical engineers who can process and analyze information adequately and propose modifications when necessary. The observational method during a long construction and operational period is a valuable opportunity to correct construction procedures whenever necessary, to adapt design and construction to eventual changes in geotechnical characteristics of the materials, to optimize operation from the technical and economic points of view, and to introduce modifications that guarantee or even improve safety conditions of the tailings dam.

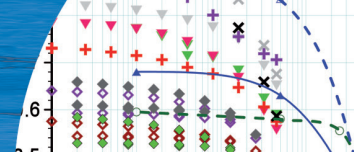


Table 1: Geotechnical instrumentation used in some of the dams (Illanes *et al.*, 2015)

Variable	El Cobre N° 4	Pérez Caldera N° 2	El Chinche	Las Tórtolas	Torito	Quillayes	Ovejería	El Mauro	Laguna Seca (*)
Flow volume, drainage S.	O	O	O	O	O	O	O	O	
Phreatic level/ PWP	C	N, V, C	C, V	C, V, F	V	C, V	C, V	C, F	F, FO
Settlements		S		E	S	S	S		E, I
Horizontal movement				E					I
Total stresses		CC							
Seismic acceleration		A		A	A	A	A	A	A
Dynamic PWP				FD		VD	VD	FD	FD

C: Casagrande piezometer, V: vibrating wire piezometer, F: fiber optics piezometer, O: weirs, A: accelerometers, E: strain gage, CC: load cell, S: hydraulic settlement gage, FD: dynamic response piezometer F, VD: dynamic response piezometer Vr, N: pneumatic piezometer, FO: distributed fiber (Ditemp), I: InSar

(*) Dam constructed using borrowed materials

Challenges presented by the long period of operation of tailings dams

Among the challenges posed by the long construction and operational periods of these types of dams are the continuity of the team in charge and the risk of failing to transmit complete design criteria and details, including the records of different designers during the operational period. The consequences of minimizing the importance of controls, and of favoring costs over technical aspects, can also be serious. These are not theoretical or speculative risks. Regrettably, the history of tailings dam failures shows that these are real risks that have caused many tailings dam failures, and consequently should not be underestimated. Mitigation measures must be developed from the time of conception of any tailings dam project.

There must be strict standards of operation and control implemented to mitigate the above mentioned risks. Such standards must be presented in a detailed Operating Manual and a complete Emergency Manual, and should be updated periodically. Responsibility for the continuous application of these manuals should rest, not only with the dam operating team but also with the upper organizational levels of the mining company, which should employ a

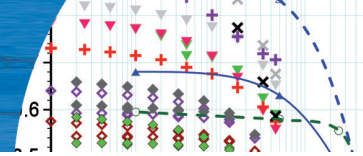
highly professional team for the purpose. The current trend adopted by some mining companies and recommended by Morgenstern (1996) and others (*e.g.* Martin *et al.*, 2002), is to employ independent professionals to inspect and supervise compliance with design criteria at all times, and ensure that any necessary modifications are undertaken in a timely manner. The following bodies should form part of the overall organization responsible for operation of the tailings dam, depending on the general upper management structure of the mining company:

A Corporate Department or internal Committee in charge of ensuring compliance with safety and environmental standards – specifically the management of mine waste – to meet both local and international regulations and those of the company itself as well as the recommendations of organisms such as the International Council for Metals and Mining ICMM, and the International Commission on Large Dams ICOLD.

A Tailings Management team, led by a competent professional with geotechnical knowledge, who reports not only to the concentrate plant operators – as is usual in many cases – but directly to the Corporate Department or Committee of the mine and to higher levels of company management. The Tailings Manager is generally responsible for operation of the whole deposit and the dam, including recovery of water from the deposit and drains and the pumping of water to the concentrate plant, as well as for dam and deposit instrumentation and controls. Eventually, operation, instrumentation, and controls can be subcontracted, but overall responsibility must be kept by the company.

A panel of external consultants, well-known specialists with wide experience in tailings deposits, that ideally participate in the project from the conceptual phase on, through detail engineering, start-up, and then during operation visiting the site at least once or twice a year. These professionals should report directly to upper corporate levels.

A Design Engineer, represented by an engineering firm or group of engineers with proven capacity and experience in tailings dams, in charge not only of design but also of general supervision, possible changes, or design improvements. In many cases the Design Engineer also acts as Engineer



of Record, this double responsibility presenting practical advantages, but also, in some special cases, it could bring some conflict of interests.

An Engineer of Record, represented by an engineering firm or group of engineers with wide geotechnical knowledge and experience in tailings dams, who would undertake periodic visits to the dam operation and issue a completely independent report on the condition of the dam once or twice per year, including clear recommendations for improvements to the procedures used, complementary studies on any critical aspects of the integral stability of the dam, or design modifications deemed necessary to ensure adequate performance of the works. In some cases the Engineer of record role is performed by specialists of the Design Engineer.

In a recent presentation, Priscu (2014) indicated that in an ideal organization, similar to the one described, there were at least 25 control activities that required analyses by experienced geotechnical engineers.

What can be foreseen in future developments of tailings dams and deposits?

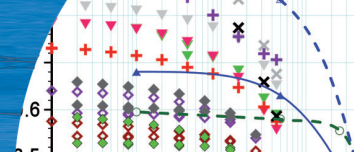
It has been clearly established that tailings sand dams constructed using the downstream and the centerline growth methods are indeed safe structures, provided they are adequately designed and operated. This conclusion also applies to very tall dams and dams subjected to high-magnitude earthquakes. Simultaneous with the development and optimization of construction and operating procedures for tailings sand dams, during the past three to four decades there have been significant efforts to develop new tailings disposal methods. These methods have had two main objectives stemming from two different incentives that may coincide in some of the solutions being developed: a) improving management of water inventories in the interior of deposits, to reduce the risk inherent in the large volumes of water the deposits could contain and b) increasing recovery of water from the deposit and/or from the tailings themselves before they arrive at the basin.

The most common measure to improve management of water for safety purposes has been, to the extent possible, to divert water not used in the transport of tailings into tunnels, auxiliary dams, canals, and pipelines. When

this is not possible, dams must be designed with enough freeboard, eventually associated with decant towers or auxiliary spillways to permit temporary storage of floodwaters that may reach the deposit. In case of a positive water balance, an auxiliary water retaining dam that could impound supernatant water remaining after tailings have settled and become consolidated, can help to maintain the lowest possible water inventory. Recently there have been proposals for the construction of separate deposits to increase the recovery of water from tailings: one deposit for sands discharged from the cycloning of 100% of the tailings, with sufficient permeability to allow recovery of excess water with relative ease; and a conventional deposit for slimes, preferably thickened to the extent permitted by available equipment. In this scheme, the deposit of sands does not require a dam. In Brazil a type of “dry sand stack” has been proposed following this general idea (Ávila, 2011).

Morgenstern (1996) referred to other depositing methods to recover water prior to the deposition of tailings, which might not require a major containment dam; he remarked: “The role of geotechnical engineering is not restricted to the design and construction of passive containment; it has much to offer in the development of new processes for waste management.” The same concept has been reconfirmed recently by the investigative committee on the failure of the Mount Polley dam in Canada (Morgenstern *et al.*, 2015).

In fact, in the last four decades, engineers have dedicated significant effort to the development of alternative solutions to the passive containment of tailings. These efforts have focused mainly on the development of thickened tailings and paste tailings using highly efficient thickeners (high density and deep cone types), as well as the development of much more efficient filters that could turn tailings into a solid form or “cake” that could be managed by conveyor belts or other massive transport systems. Up to now, these solutions have had relative success only for small daily productions, up to approximately 30000 metric tons of mineral treated per day TMPD. Recently, starting in 2010, two interesting experiences with thickened tailings disposal have been carried out in two different copper mines in the North of Chile for daily production of more than 100000 TMPD each. In both cases, there were serious problems due to the failure to predict the characteristics of the paste when deposited in such large volumes, mainly regarding the



deposition slopes and the efficiency of thickeners. There were also problems with the changes of the characteristics of the thickened tailings flows. These problems have not yet been fully resolved even after considerable delays in the startup of the projects and investment in new equipment and new site preparation. These two courageous projects certainly will allow a more accelerated development of these technologies. Future detailed analysis of these two major tests of the thickened tailings disposal in two large operations will be of great importance for the development of this technology.

In order to overcome the uncertainties involved in a thickened tailings solution for a large copper project with production of over 120000 TMPD, an interesting idea has been proposed by consultant Andrew Robertson during the feasibility study for this project: to consider a “Conventional Impoundment & Thickened Tailings” or CITT in which uncertainty about the behaviour of thickened tailings would be resolved by beginning a conventional deposit with a dam constructed out of borrowed materials and/or sands. The dam could then reduce its rate of growth as thickeners developed greater levels of efficiency, including use of future equipment with a higher thickening capacity. In this case it has been critically important to predict the amount of water recovery to be attained in moving from conventional deposition to thickened tailings, to ensure the volume of flow of fresh water required by the concentrate plant.

In the case of filtered tailings the possible construction of the Rosemont project in the USA would be an opportunity to verify the operation of a major tailings filtering system and the deposition of the tailings “cake” for a production of 75000 TMPD (Newman *et al.*, 2010). As the problems of the use of these technologies for large productions are not fully resolved, basic research is still needed on the rheology of thickened tailings and paste, and further equipment such as thickeners, filters and pumps needs to be perfected or developed. Also, the very large and relatively shallow deposits of paste or filtered tailings will have to be deposited in relatively flat areas not always available in mountainous regions where many large mines are located. The vulnerability of these extremely large deposits to intense rains and earthquakes must also be investigated.

In the conventional tailings deposits, there is also room for the investigation of different possible methods that could

accelerate the consolidation of deposited tailings and slimes, turning a low density, semi-viscous material into a more solid mass, eliminating the risk posed by an easily flowing material at the same time water recovery is increased. Possible methods such as combination of drains and vacuum pumps, electro-osmosis, use of chemicals, and eventually even bacterial treatments should be investigated among others.

Finally, the alternative of depositing tailings in the ocean cannot be left out. This may represent the definitive solution not only for current operations, but also for the closure of large tailings deposits in many mining countries, especially Chile and Peru. It will be necessary to study this alternative in detail by conducting complete technical, economic, and environmental feasibility studies.

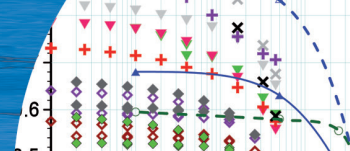
Final comments and conclusions

Tailings dams are built and operated over a considerable period of time, thus presenting clear opportunities to apply the observational method in order to improve and optimize construction and operation. A suitable instrumentation network and control system must be implemented from the beginning of construction and up through the post operation and closure periods. Periodic analysis of the collected information has to be carried out by experienced geotechnical engineers.

The extremely long life cycle of tailings dams presents an important challenge for the management of the tailings deposit and of the dam, or dams, containing those tailings and slimes, due to the frequent turnover in personnel and organizational management. This runs the risk of original design criteria being misinterpreted or ignored, of monitoring and control schemes being reduced or interrupted, eventually due to operational costs cut. A long term corporate policy must be put in place to ensure continuity of appropriate management.

The current international trend is for tailings management to report directly to the highest level in the mining company and to have a periodic independent audit of the operation by a panel of experts, the design engineer, and the Engineer of Records, which should conduct a complete analysis of the tailings deposit and tailings dam at least once a year.

Although engineers have been dedicating considerable effort to the development of alternative technologies to



the conventional deposition of tailings, such as thickened and filtered tailings – an effort that continues today with a sense of urgency – the fact is that many tailings sand dams, downstream and centreline, have been built in the last four or five decades with sound design principles, and many others will be built in the next years, all of them under operation or just finishing operation. The study of their performance, as well as the research on different aspects related to the physical, chemical, and geotechnical characteristics and behaviour of tailings, slimes, sand and gravel or rock-fill, must continue in order to ensure adequate performance in the long term, including closure.

The important development of the metallic mining industry in the last two decades, the continuous growth expected in the near future, and in consideration of the increasing restrictions on large tailings deposits on land, studies and research on thickened and paste tailings as well as filtered tailings have to continue. The same is valid with regard to a possible disposal of tailings in the ocean. This last alternative could become an adequate solution, if feasible from the environmental point of view, considering the huge volumes of tailings already accumulated and it will continue being accumulated in all mine countries. Only in Chile more than 2.5 Mt of tailings need to be deposited daily.

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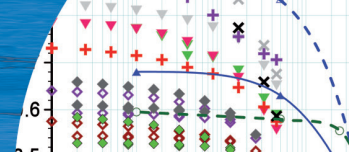
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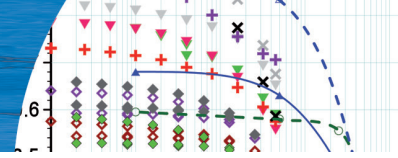
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