Risk minimisation in construction of upstream tailings storage facilities based on in-situ testing

Minimisation du risque sur base d'essais in situ lors de la construction de digues de stockage des résidus miniers par la méthode amont.

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ABSTRACT: Tailings storage facilities (TSFs) in Chile are now built using the downstream method of construction, an approach that was triggered by the failure of a number of upstream constructed facilities during or immediately after large seismic events. In Australia, the upstream method continues to be used, because of the significantly lower cost and the perceived lack of a credible seismic risk. The design of TSFs in Australia is moving towards the adoption of maximum credible earthquake (MCE) considerations, particularly for closure, where the design life is increasingly expected to be 'in perpetuity'. Recent research in Chile has shown the viability of using a lightweight penetrometer, the PANDA penetrometer, as a tool for rapid, inexpensive and regular in-situ determination of the state of deposited tailings. The PANDA has been calibrated against density measurements and is frequently used to estimate the relative density, which is a useful indication of liquefaction susceptibility. This paper describes an approach for managing upstream TSFs in Australia using the PANDA penetrometer for regular in-situ testing which, when coupled with the results of laboratory compressibility measurements, can be used to predict the future state of tailings once buried to a significant depth.

RÉSUMÉ : Aujourd'hui les digues de stockage de résidus miniers (DSR) au Chili sont construites par la méthode aval, une approche qui a été déclenchée par la rupture de plusieurs ouvrages contruits par la méthode amont, pendant ou immédiatement après d'importants événements sismiques. En Australie, la méthode amont continue d'être utilisée, du fait de son moindre coût et de la perception de l'absence de risque sismique crédible. La conception des DSR en Australie avance vers l'adoption de considérations d'un tremblement de terre maximum crédible, en particulier dans le cas de fermeture de site minier, pour laquelle la durée de vie de l'ouvrage est considérée être à perpétuité. Des recherches menées au Chili ont montré qu'un pénétromètre léger, le pénétromètre PANDA, peut être utilisé comme outil pour déterminer l'état des résidus déposés dans les digues, de manière rapide, peu coûteuse et régulière. Le PANDA a été étalonné vis-à-vis de mesures de densité et est utilisé fréquemment pour estimer la densité relative, donnant ainsi une indication de la tendance à la liquéfaction. Ce papier décrit une approche de la gestion des DSR en Australie basée sur des essais in situ réguliers à l'aide du pénétromètre PANDA qui, combinés aux résultats de mesures de compressibilité en laboratoire, permettent de prédire l'état atteint par les résidus une fois enfouis à une certaine profondeur.

KEYWORDS: tailings, liquefaction, earthquake, penetrometer, in-situ testing.

1 INTRODUCTION

Tailings storage facilities represent some of the largest man-made structures in the world, with many reaching heights in excess of 100m and volumes in excess of 1 billion cubic metres. The risks associated with these facilities are associated with the storage of large volumes of material that is often at a very low density. Loading due to events such as earthquakes can be particularly devastating for these facilities, and there are numerous records of failures of Tailings Storage Facilities (TSFs) resulting from earthquakes. Nowhere has this been more apparent than Chile. In Chile, failures have mainly occurred due to seismic liquefaction, followed by slope instability and, in some cases, overtopping. These failures have mainly been in operational tailing dams constructed using the "upstream" method, located in areas with an average rainfall regime, including Valparaíso, Santiago, Rancagua (central zones) and Maule (southern-central), (ICOLD 2001, Carvajaly and Pacheco 2005, and Rico et al 2008).

Failure of the El Cobre TSF, which occurred in 1965, resulted in the deaths of more than 300 people. A consequence of this failure was significant changes to the practice of tailings management in Chile, with the tendency to adopt downstream construction as the preferred method of construction. This trend accelerated after the failures in Chile in 1985, which resulted in further fatalities. Today, no new large TSF in Chile is constructed using the upstream method, although this is not necessarily true for some of the smaller operations. The very large earthquake that occurred in 2010 (magnitude 8.8), resulted in the failure (due to either slope instability or liquefaction) of five TSFs, all of which had been built using the upstream technique; of these, only one was operational at the time of the earthquake. The other four could be considered to have been in a state of closure, indicating that the risks associated with upstream construction do not necessarily go away once operations cease. There were no failures of downstream TSFs, although anecdotal evidence suggests that in some cases the contents of the TSF (consisting of cyclone overflow usually) did indeed liquefy, but the downstream shells retained their integrity.

2 AUSTRALIAN PRACTICE

The upstream method of construction is still the most common method of TSF construction in Australia. This is justified on the basis that levels of seismicity in Australia are generally low and there have been no recorded failures of TSFs in Australia due to earthquakes. The relatively low cost of this approach is a strong consideration for its continued use.

Events such as the failure of a number of non-operating TSFs during the 2010 earthquake in Chile have recently focused attention in Australia on the adequacy of current design approaches in the country. A number of peer review exercises led by tailings experts from outside Australia have highlighted potential concerns with techniques used for both design and monitoring. In addition, the recently released ANCOLD

(Australian Commission on Large Dams) document entitled, 'Guidelines for the Design, Construction, Operation and Closure of Tailings Dams' recommends that the design earthquake should be the Maximum Credible Earthquake (MCE). Concurrent with the ANCOLD tailings document (which is a revision of the 1999 version), the ANCOLD 'Guidelines for the design of dams for earthquake' are also being revised. This latter document provides advice on design earthquakes, and although at the time of writing the final version had not yet been released, implications of the document are that for a large proportion of the country where mining occurs (and thus TSFs occur), design earthquakes will exceed 7.4 magnitude.

There is understandably some concern that current practices might be found wanting, should a large seismic event occur. Similarly, there is increasing recognition that simple, robust and inexpensive techniques for evaluating susceptibility to failure of TSFs due to earthquake loading is highly desirable. This paper suggests such a technique, and describes a proposed procedure for ongoing monitoring and testing that will reduce uncertainties associated with current practices.

3 MONITORING OF IN-SITU STATE

The key factor determining the susceptibility of tailings to liquefaction during a seismic event is the in-situ dry density of the tailings, and how the in-situ value relates to parameters such as the maximum and minimum dry density for the same material. These latter parameters are determined in the laboratory using standard procedures. If tailings are sufficiently dense (close to the maximum dry density), they will dilate upon loading, thus generating negative pore water pressures. Liquefaction is not a risk under these conditions, even under prolonged cyclic or dynamic loading (although significant displacements might still occur). Any programme of in-situ testing should therefore focus on determination of the in-situ density, and indeed more importantly the in-situ state, where 'state' is a measure of the difference between the in-situ density and the density at some, previously defined condition. This latter condition is usually defined by the Steady State Line (SSL), where the SSL defines the combination of void ratio and effective stress (either vertical or mean values) which renders the material in question either susceptible to liquefaction (contractive behaviour) or not susceptible (dilative behaviour). There is a large amount of literature on the laboratory testing of tailings to determine the SSL, but relatively little on techniques to determine state in-situ. One major exception is the work by Jefferies and Been (2006).

There are a range of techniques to measure in-situ parameters such as strength and density, including boreholes with laboratory testing of (supposedly) undisturbed samples, sonic testing, cone penetrometers, piezocones, dilatometers, SPT, or a range of seismic techniques. The currently preferred approach to determining in-situ state is the use of the piezocone. The disadvantages of this technique, especially when working with mine tailings, are cost, availability and access. Many mine sites in Australia are relatively remote and in order to conduct a piezocone testing campaign requires much forward planning and scheduling, particularly with the limited availability of suitable equipment. In addition, there is the need to be able to carry out tests on a regular (perhaps weekly) and ongoing basis during construction operations, such as during an upstream wall lift. The PANDA lightweight penetrometer provides a potentially valuable alternative technique, although it is certainly not as versatile as the piezocone device, because it cannot measure pore water pressures.

3.1 *The PANDA penetrometer*

The PANDA was developed in France (see Chaigneau et al, 2000) and is a lightweight, highly portable, dynamic penetrometer that is conventionally used in quality control applications, particularly compaction control for cohesionless materials. It is very quick to set up and can be used by a single operator. The portability has been found to be particularly useful when accessing sloping terrain, such as the downstream face of a TSF. It is a variable energy device (where the energy is simply derived from the force of the hammer blow to the anvil) and can be used for very loose deposits, as well as to detect layering in deposits containing both dense and loose layers (such as some TSFs). It has been used extensively in Chile and is now one of the most widely accepted techniques by regulators in that country for quality control of the compaction of downstream TSFs.

Results from an extensive testing campaign on three different copper TSFs in Chile are shown in Figure 1, where the PANDA tip resistance is designated as q_d.

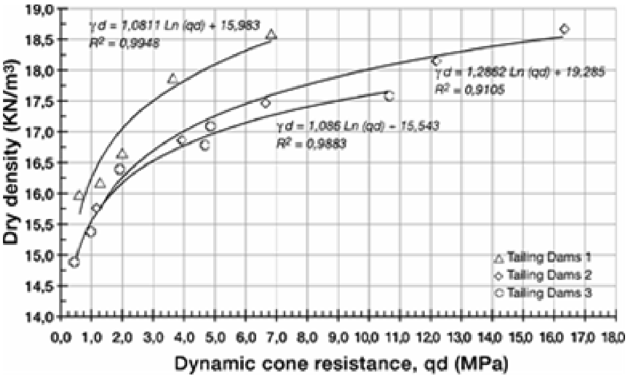

Figure 1. Demonstration of results obtained with PANDA penetrometer on three different tailings storage facilities. Note the difference in cone resistance for the same value of density.

From the results shown in Figure 1, it appears that there is no unique relationship between dry density and cone resistance; rather, this relationship appears to be dependent on the nature of the tailings tested. Further investigation showed significant variability between the tailings obtained from the three TSFs in question. Figures 2 and 3 illustrate this variability, in terms of mean particle diameter (d_{50}) and percentage fines (in this case defined as < 80μm) respectively.

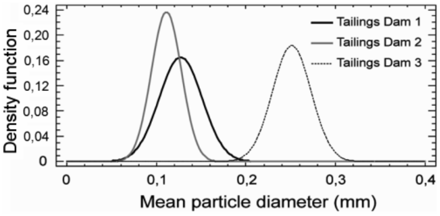

Figure 2. Variability of tailings from three different TSFs; variability measured in terms of mean particle size.

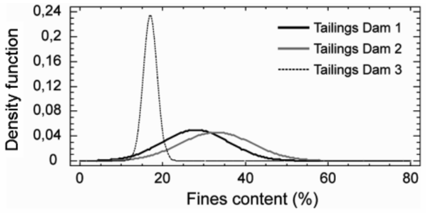

Figure 3. Variability of tailings from three different TSFs; variability measured in terms of percentage finer than 80μm.

These results emphasise the need to carry out site-specific correlations between PANDA tip resistance and relative density. A universal correlation clearly does not exist. This is not a particularly restrictive consideration, as a typical TSF will be constructed over a number of years and any changes in the physical characteristics of the tailings are likely to be incremental, meaning that appropriate correlations can be regularly updated.

Given that the maximum depth of testing achievable with the PANDA is about 7m, there is a question about the applicability of the method to large, deep tailings deposits. Although the 7m depth restriction is certainly a limiting factor for existing deposits deeper than 7m, the PANDA technique can be used in conjunction with conventional compression testing to predict the tailings state for future, deep deposits of tailings, as explained below.

4 USING PANDA DATA TO PREDICT FUTURE INSTABILITY RISKS

Aside from the material beneath the outer slopes, all the tailings in a TSF will be subjected to essentially one dimensional compression. Conventional oedometer tests can therefore be used to simulate the likely change in void ratio that will occur when a TSF is built to full height. If PANDA tests are carried out on the initial layers of tailings (before they reach a depth of 7m or more), the initial state will be well defined (as long as appropriate correlations have been established) and reasonable predictions may be made as to how the state will change as the TSF is constructed.

This idea was argued in some detail by Park and Byrne (2004), who used data from compression tests on eight different sands and derived an expression relating relative density D_r and vertical effective stress σ'_v through:

$$D_r = D_{r0} + \alpha \sqrt{\sigma'_v / P_a}$$

where P_a is atmospheric pressure, D_{r0} is the initial relative density and α is a parameter that is a function of the maximum and minimum void ratios and a sand stiffness number C that is independent of void ratio.

As relative density is directly related to void ratio, the above equation makes it possible to predict the void ratio at any depth in a TSF profile at some time in the future, if accurate estimates of starting in-situ values are available. It is suggested that these initial values may be obtained using PANDA penetrometer tests. During the initial phases of tailings deposition, it should be possible to carry out a number of field testing campaigns at particular locations, obtaining information over a number of years. These data can be used to verify that the PANDA data from one campaign to another are consistent with the predictions made using oedometer data.

These tests should be complemented with triaxial or simple shear tests to define the relationship between void ratio and effective stress (the Steady State Line discussed by Jefferies and Been (2006)), amongst others. Integration of these various data will provide a consistent methodology for estimating the liquefaction susceptibility of a TSF both at the time PANDA tests are undertaken, and in the future.

The potential value of using conventional oedometer tests to predict future relative density values (knowing initial in-situ state) can be illustrated by consideration of data presented by Park and Byrne (2004). They showed that different sandy materials placed at the same initial relative density will not necessarily consolidate (compress) to the same relative density, even if subjected to the same overburden stress. This might be counter-intuitive, as it is commonly considered that tailings near the bottom of a TSF is much less prone to liquefaction than tailings near the top (where the confining stress is lower). However, data presented by Park and Byrne (2004) for Brasted sand placed at a relative density of 50% compressed to a final relative density value of only 57% under a vertical confining stress of 1000kPa. A relative density threshold of around 60% is often considered a reasonable first-pass estimate of the boundary between potentially liquefiable and non-liquefiable tailings, implying that the Brasted sand quoted above might still be susceptible to liquefaction at a depth of around 50m to 60m. Other data presented by Park and Byrne (2004) showed results that are more consistent with current expectations. Tests on Quiou sand placed at a relative density of 50% compressed to a value of 80% under a vertical effective stress of 1000kpa. This value of relative density is highly likely to render the Quiou sand non-liquefiable at higher confining stresses, as is expected using current concepts.

A key factor in the above discussion is the relative slopes of the oedometer compression line and the Steady State Line for a particular tailings. If they are equal for example, then tailings placed at low relative density (which renders it susceptible to liquefaction) would remain so, even under high confining stresses. Unfortunately the work of Park and Byrne (2004) did not investigate the response of the sands to shear (they utilised data from the literature), so it is not possible to make these comparisons for their data. However, data of this type is likely available in many consultants' internal databases, and interogation of this data could prove extremely valuable.

5 POTENTIAL LIMITATIONS TO USE OF PANDA PENETROMETER TESTING

Use of the PANDA penetrometer for routine testing of the state of tailings is now commonplace in Chile, where it has in fact effectively been written into legislastion. Recently revised Chilean legislation governing the construction and operation of TSFs specifically mentions the PANDA technique as one of the preferred approaches for density control on TSFs. Given the increasing awareness of the critical importance of correctly controlling density, and the increasing acceptance by regulators of the approach, it is important to consider potential limitations of the technique before advocating its widespread adoption.

5.1 Site-specific correlations

As shown in Figure 1, the relationship between relative density and penetration resistance varies with the material tested. This in itself is not a major problem; it simply requires that adequate correlations be established, with the obvious techniques being calibration chambers or in-situ correlations in which the field density is measured using techniques such as the sand replacement method. A potential limitation is that the tailings produced by a particular mine may change with time, as milling rates change or the nature of the ore being mined changes. Established correlations might then no longer be valid. However, through index tests such as particle size distribution tests, it is possible to monitor such changes in the nature of tailings being produced, and simply carry out new correlation studies. It will only be once experience is gained at a particular operation that the required frequency of these re-calibrations will become apparent.

5.2 *Effect of moisture content*

Results from a preliminary set of tests using a 0.5m diameter, 0.75m deep calibration chamber are summarised in Table 1. The tests were carried out on a medium sand having a d_{50} of 280μm.

Table 1. Relationship between water content and PANDA resistance for a medium sand prepared at 60% relative density.

Water content (%)	0	4	8	12	25
Resistance (MPa)	0.66	3.56	2.37	1.77	1.34

The very low resistance at zero water content is essentially irrelevant for the application under discussion, as all tailings are placed in either a fully saturated, or a moist state. All large mining operations in Chile now utilise the downstream method of construction, in which the tailings stream is split into a coarser fraction (the underflow), used for construction of a compacted embankment, and a finer fraction that is placed behind the constructed embankment. The underflow is usually placed at water contents of around 6 to 10%. At these values, the variation of PANDA resistance is less severe (as shown in Table 1) for material that represents the coarser end of tailings from Chilean copper mines. It may be for this reason, reinforced by the reproducible nature of material prepared using mechanical cyclones, that the PANDA has found such widespread application in Chile. In jurisdictions such as Australia, where the upstream (rather than the downstream) method is widely used, tailings are placed as full-stream tailings, and any segregation that occurs is due to natural sorting processes that occur on the tailings beach. The water content is also likely to be more variable than tailings placed used the downstream technique, so the type of results shown in Table 1 may be much more important. Much more work clearly needs to be done to determine the effect of initial moisture content on penetrometer resistance for a range of tailings types.

6 DISCUSSION

The mining industry is acutely aware of the need to continuously strive to minimise risks associated with all aspects of its operations. Failures of TSFs still occur with unacceptable regularity. There is at least one major failure per year somewhere in the world. The consequences of a TSF failure can be catastrophic, with multiple fatalities often occurring and significant environmental damage being almost assured. Therefore any procedures that can be implemented to reduce the likelihood of such events are likely to be embraced by the industry, as long as the outcomes are consistent, not prohibitively expensive and readily available.

The PANDA penetrometer provides an approach that potentially satisfies these requirements. It has the major advantage of portability, as it can be carried, set up, and operated by a single operator, relatively little training is required, and the test itself is quick. It means that multiple profiles can be tested in a single day, tests can be carried out on embankment slopes (unlike most machine-mounted penetrometers) and the equipment is relatively inexpensive.

Disadvantages are that, outside of Chile, the equipment is unproven in application to tailings facilities. Sensitivity to in-situ moisture content is also not well understood and requires significant further study. However, given the potential advantages of the method, it is certainly something that is worth pursuing and it is to be hoped that suitable field study sites can be found to investigate the method fully.

7 CONCLUSIONS

Risk minimisation is a key consideration for all mining operations. Perhaps because they are not part of the profit chain, tailings storage facilities, and the stability of these facilities, does not always receive the attention they warrant. With decreasing mineral grades, coupled with more and more efficient mining methods, the volume of new TSFs continues to grow apace. The potential consequences of failure of one of these facilities grows in a similar fashion, and any technologies that might help reduce the potential occurrence of a TSF failure is worthy of consideration. Such a technology, it is suggested in this paper, is the use of a relatively simple penetrometer, the PANDA penetrometer.

The PANDA penetrometer is now widely used and accepted in Chile. The experience gained in this country should be investigated and the potential application to other jurisdictions determined. It will be necessary to carry out extensive confirmatory studies, which must include thorough investigations of the effect of in-situ moisture content on penetrometer resistance.

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