Stability of chilean's tailings dams with the Panda® penetrometer. Experiences of the last 10th

Dix ans d'études de la stabilité des barrages de résidus miniers chiliens à l'aide du pénétromètre Panda®

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ABSTRACT: In Chile, since the beginning of the 20th century, about 40 cases of mechanical instability of the tailing dams have been reported mainly due to liquefaction, slipping of banks or settlement. In order to solve this problem, a scientific and technological cooperation has been established in 2001 between the geotechnical of groups at the Catholic University of Valparaíso (Chile) and Blaise Pascal University Clermont-Ferrand (France) whit the support of two companies, Sol-Solution in France and Geotecnia-Ambiental in Chile. This article presents the main results that have allowed to propose a methodology for control and diagnosing of tailing dams and its application in the medium mining sector. It is based on in-situ determination of geomechanical parameters (internal friction angle and density index) using the Panda® lightweigh penetrometer in order to characterize the constituent materials, the variability of these materials and their implementation in the works. Finally, this methodology allows taking into account this variability in the study of stability and the risk of liquefaction of these structures in a probabilistic approach.

RÉSUMÉ: Au Chili, depuis le début du XXe siècle, environ 40 cas d'instabilité mécanique de ces dépôts, principalement par liquéfaction, glissement des talus et tassements, ont été rapportés. C'est dans ce contexte et pour apporter une réponse à ce problème, qu'une coopération scientifique et technologique a été établie en 2001 entre les groupes de géotechnique de l'Université Catholique de Valparaiso (Chili) et de l'univeristé Blaise Pascal Clermont-Ferrand (France), avec le soutien des entreprises Sol-Solution (France) et Geotecnia Ambiental (Chili). Cet article présente les principaux résultats qui ont permis de proposer une méthodologie pour le contrôle et le diagnostic des barrages de résidus miniers de relave ainsi que son application au secteur de l'industrie minière moyenne. Elle s'appuie sur la détermination in situ des paramètres géomécaniques (angle de frottement interne et densité relative) à l'aide du pénétromètre Panda® en vue de caractériser les matériaux constituants, de la variabilité de ces matériaux et de leur mise en œuvre au sein des ouvrages. Finalement, cette méthodologie permet de prendre en compte cette variabilité pour l'étude de la stabilité et du risque de liquéfaction de ces ouvrages dans une approche probabiliste.

KEYWORDS: soils and site investigation, structures in seismic areas.

1 INTRODUCTION

Mine tailings are frequently stored in dams. This is the case for copper for which the coarse fraction (fine sands) of the tailings form the body of the dams, while the fine saturated fraction (sludge and silts) is poured by cycloning into the reservoirs of the dams thus formed.

Chile has a very large number of tailings dams built in this way. Due to the construction methods and materials used, these dams comprise failure mechanisms such as loss of stability, liquefaction, and internal and external erosion leading to major risks for the populations and their environments. Such risks are highlighted by the accidents that have occurred around the world and recently in the case of failures occurring during the earthquake of 27 february 2010 in Chile, with fatal consequences (Dobry and Alvarez 1967, ICOLD 2001, GEER 2010). In order to manage these risks, it appears necessary to employ a probabilistic approach to predict their behaviour during construction and after closing. However, applying such an approach in practice at present is limited by the difficulty of managing the data (random variables and stochastic fields) to be introduced in the reliability calculations for the limit conditions involved and conditioned by the relevance of the probability models chosen to represent the variability of tailings dam properties (Villavicencio et al. 2011). This is the reason why, this article presents an approach of estimating calculation parameters (friction angle ϕ' and density index ID%) governing the stability of these dams, and its variability from dynamic penetration tests. Then models are proposed for all dams composed of the same mine tailings types, making it possible to link a probability law to the calculation parameters ϕ' and ID%. This method, applied to Chilean dams constructed from copper mine tailings, proposes a single model for all tailings dams so as to associate a probability law to the ϕ' and ID%.

2 ESTIMATION OF THE DENSITY INDEX (ID%) AND THE FRICTION ANGLE (ϕ')

1.1 *The objective*

In mine tailings with non plastic fine particles (size < 80 µm) ID% and ϕ' are very important parameters, related to the in situ penetration strength (N, qd, qc, etc), the input parameter of static and dynamic stability models and for the evaluation of the liquefaction (Troncoso 1986). These parameters are greatly influenced by the origin and mineralogy of the particles, by the physical characteristics and state of arrangement of the grains determined by the state of compacting and by the extent of stresses in-situ (Bolton 1986).

The methods used to implement mine tailings lead to the prevalence of stratified internal structures that can be heterogeneous. This can result in variations of resistance properties, especially ϕ' and ID%, as a function of depth. Thus it is important to estimate the values and variability of these parameters. To do this, we propose an estimation method based on measuring the dynamic cone resistance (qd) that can be relatively easily measured on this type of structure.

1.2 *Normalisation of qd*

Estimating ID% and ϕ' by using empirical and semi-empirical relations, first implies normalising qd at a reference stress corresponding to atmospheric pressure (pa), using the following equation 1.

$$qd_{N1} = qd \cdot C_q \quad \text{with} \quad C_q = \left(p_a / \sigma'_v\right)^c \qquad (1)$$

where: qd_{N1} is the dimensionless normalised dynamic cone resistance, qd is the dynamic cone resistance, pa is the atmospheric pressure, σ'_v is the effective vertical stress, "c" is the normalisation coefficient (0.5 to 0.75).

According to Moss et al. (2006), this reference stress value is considered as reasonable if the depth/stress relation is taken into account. According to Salgado et al. (1997) and Moss et al. (2006), the normalisation coefficient is not only linked to the intrinsic properties of the soil such as the type of grain and the physical characteristics of the material (mineralogy, granulometry, particle shape and texture characteristics), lateral pressure (K_o), compressibility, cementation, resistance to crushing of the particles, etc.

1.3 *Experimental approach*

Our study is based on the use of cone penetration resistances (qd) obtained by using the Panda test. The Panda device is a manual light dynamic penetrometer with variable energy and a small cone section (2.0 or 4.0 cm^2) (Gourvès et al. 1997, Benz 2009). The Panda provides the cone resistance qd of the soil as a function of depth, and is capable of performing a large number of in situ tests thanks to its small size and its quick implementation. This device can operate until 6.0 (m) in depth and for materials having particles size lower than 50.0 (mm).

Table 1. Geotechnical properties of mine tailings. Values and statistical analyses of experimental data from three representative tailings dams.

Geo. Prop	No. 1		No. 2		No. 3	
	Av.	CV	Av.	CV	Av.	CV
γ_s	3.09	4.6	3.36	8.0	3.1	2.2
D_{50}	0.13	19.0	0.11	15.2	0.25	8.7
F.C	28.0	28.7	33	26.3	17	10.0
IP	0	0	0	0	0	0
γ_{dmax}	18.2	6.2	20.8	8.0	18.5	2.3
γ_d	17.5	6.6	20.1	8.2	18.1	2.9
w_{nat}	11.0	22.3	3.3	43.1	7.5	27.3
qd	4.8	50.6	2.87	45.9	1.95	52.8
N_{60}	22	62.5	12	58.8	-	-

γs: specific weight (kN/m^3), D_{50}: median diameter (mm), F.C: percentage of fines less than 80 (μm), IP: plasticity index (%), γdmax: Proctor dry density (kN/m^3), γd: dry density in situ (kN/m^3), w_{nat}: water content in-situ (%), qd: cone resistance PANDA test (Mpa), N_{60}: corrected penetration resistance index, Av: average, CV: coefficient of variation (%).

A serie of Panda tests have been performed on the mine tailings coming from three dams studied, under controlled laboratory conditions in a calibration chamber. The following procedure was used:

a) Determination of the physical characteristics of 3 samples of mine tailings of copper sulphates (Table 1).

b) Performing dynamic cone resistance tests in a calibration mould for different states of density to obtain the relation γd/qd (calibration curve). A logarithmic relation can be observed, in agreement with previous results (Chaigneau et al. 2000) for this type of material. Figure 1 gives the calibration curves γd/qd obtained for dams No. 1, No. 2 and No. 3.

c) Normalisation of qd at atmospheric pressure (equation 1).

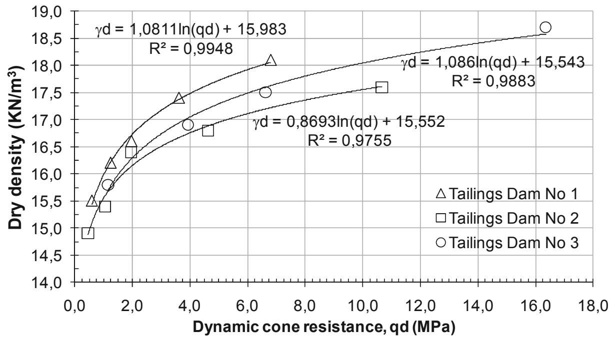


Figure 1. Relation γd/qd for tailings dams No. 1, No. 2 and No. 3 in the study.

1.3.1 *Relation ID% = f (qd_{N1})*

The equivalence between the state of density (% Optimum Proctor Normal) and ID% was estimated for each calibration test. On the basis of the normalised cone resistance (qd_{N1}), and by considering the classification modified by Skempton (1986) and adapted by Villavicencio (2009), we estimated ID% associated with each degree of compaction (table 2).

Table 2. Estimation of the state of compaction and associated mechanical behaviour for silty sands. Villavicencio (2009).

qd_{N1}	ID%	State of compaction	Mechanical behaviour	Liquefaction potential
0 – 17	0 – 15	Very low	Contractant	High
17 – 69	15 – 55	Low	Contractant	High
69 – 82	55 – 60	Average	Contractant /Limit	Limit
82 – 162	60 – 80	Dense	Dilatant	Null
162 – 326	80 – 100	Very dense	Dilatant	Null

Studies conducted by Troncoso (1986) have concluded that for mine tailings with a percentage of fines around 15% , with confining stresses between 50 kPa and 350 kPa, ID% below 50%-60% is an indicator of contractancy. Under this condition, if the material is saturated or partially saturated, under seismic conditions, the risk of liquefaction is real. On the other hand, the material will tend to a dilatant behaviour for a relative density over these values. Verdugo (1997) have conducted an analysis of the variation of the minimum and maximum densities (Vibratory and Proctor compaction) both with mine tailings and similar soils (sands and silts) with different percentage of fines. They conclude that in situ ID% of 60% is a very reasonable compaction value with a satisfactory mechanical behaviour (dilatancy) in structures that allow certain degree of deformation such as the tailing dams.

An empirical model was adapted by using a simple regression on all the pairs of experimental data (qd_{N1}, ID%) for the three samples of mine tailings. Since we consider that mine tailings can be globally classified in a single geotechnical class, it is possible to estimate ID% as a function of the resistance qd_{N1} by a single relation. The model used is given by the following equation:

$$ID\% = 28.5 \cdot \ln\left(qd_{N1}\right) - 65.4 \quad \text{with} \quad 10.0 \leq qd_{N1} \leq 326.0 \qquad (2)$$

Figure 2 shows that the results of the model are very close to the experimental results. In addition, the relation proposed by Tatsuoka et al. (1990) was used by replacing qc_{N1} by qd_{N1}.

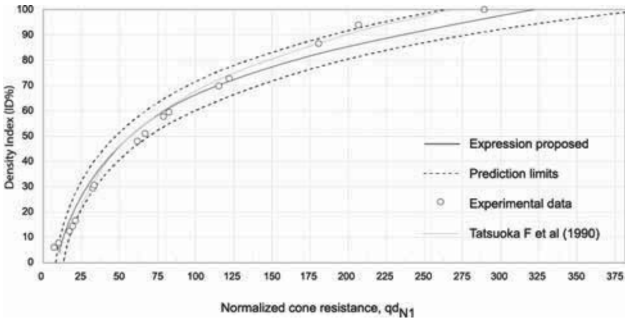


Figure 2. The experimental points, relations proposed and references for estimating the ID% of mine tailings as a function of qd_{N1}.

1.3.2 *Relation $\phi' = f(qd_{N1})$*

Since we considered that mine tailings can be globally classified within one geotechnical class, it is possible to estimate ϕ' as a function of the resistance of qd_{N1} by a single relation. To do this, a regression analysis was performed on all the pairs of experimental data (qd_{N1}, ϕ') obtained during the calibration tests, for the three samples of mine tailings (figure 3). The model used is given by the following equation:

$$\phi' = 14.79 + 5.54 \cdot \ln(qd_{N1}) \quad \text{with} \quad 10.0 \leq qd_{N1} \leq 280.0 \qquad (3)$$

As it can be seen on figure 3, the results of the model are very close to the experimental results. In addition, the relation proposed by Díaz and Rodríguez-Roa (2007) was used by replacing qc_{N1} by qd_{N1}.

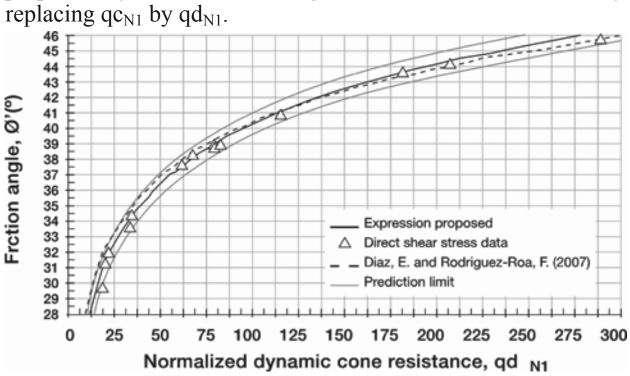


Figure 3. Experimental points, proposed and bibliographic relations for estimating ϕ' of mine tailings as a function of the qd_{N1}.

This result is in full agreement with the works already carried out on the correlation between qc and qd obtained with a Panda penetrometer. Indeed, it has been proven (Chaigneau et al. 2000, Lepetit 2002) that in the case of sands and silty sands, the average value obtained for the ratio qd/qc is equal to 1.03. More recent research performed by Rahim et al. (2004) confirmed the relation between qd and qc. Their results obtained for granular soils have been demonstrated experimentally and analytically on the basis of the cylindrical cavity expansion theory and that of cavitation collapse.

The resistance qd obtained with a light Panda penetrometer can therefore be assimilated with qc. In conclusion, in the case of mine tailings:

(1) density index (ID%) and effective friction angle (ϕ') can be deduced very precisely from the normalised cone penetration resistance qd_{N1} by a two single relations,

(2) relation $qd_{N1} = qc_{N1}$ is very well validated which allows using either static or dynamic penetrometers according to need.

1.4 *Application case: density index (ID%) and associated mechanical behavior*

On the basis of equation 2, it is possible to estimate the profiles of the density index (ID%) as a function of depth from the penetrometric tests performed in situ. The adaptation of the correlation presented in table 2, allows estimating the mechanical behaviour of mine tailings as a function of ID%. At global scale (measurements processed at the scale of the tailings dam by using the ID% distribution obtained from all the penetration tests performed), the distribution of all these ID% values for each dam can be adjusted by a normal law (Figure 4).

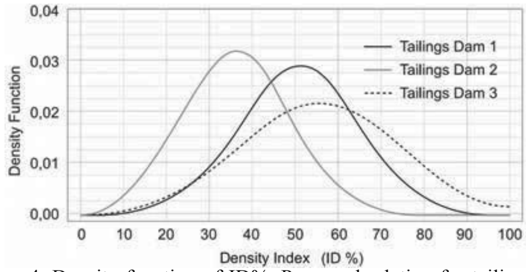


Figure 4. Density function of ID%. Proposed relation for tailings dams No. 1, No. 2 and No. 3 in the study.

At global scale, the density function makes it possible to obtain a global idea of the mechanical behaviour of the mine tailings stored, by considering the limit value of ID%, which permits classifying contractant or dilatant behaviour and associate in a qualitative way the liquefaction potential. As an example, table 3 presents a probabilistic analysis in global scale of the variability of ID% and the mechanical behaviour for the tailing dam No.1.

Table 3. Density index (ID%) and associated mechanical behaviour. Analysis at global scale. Tailings dam No. 1.

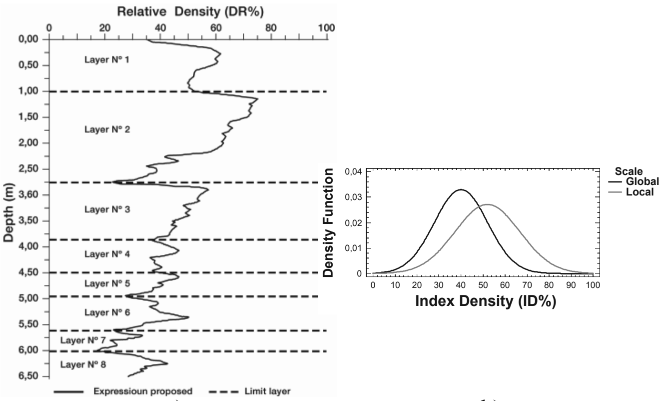
ID%		Analysis of the mechanical behavior				
Av.	C.V %	ID%	% of values	State of compaction	Mechanical behaviour	Liquefaction potential
52	28.3	< 55	58	Low	Contractant	High
		55 – 60	13	Average density	Contractant /Limit	Limit
		60 – 100	29	Dense to very dense	Dilatant	Null

At a local scale (measurements processed at the scale of each penetration test, by using the ID% distribution), the distribution of all these ID% values can then also be adjusted by a normal law (figures 5a, 5b). The so-obtained results are consistent with the compaction test performed during the construction of the three tailings dams.

The results are similar for the three dams, they show that a local test can be used to estimate ID% for each penetration test, with sufficient precision provided that the calibration tests have been carried out on the material characteristics of the dam at the scale of the structure concerned. The variability of ID% and the soil mechanical behaviour associated, allows to estimate in a first stage, the liquefaction potential of tailings dams in both scales, global and local, and identify in a local scale the zones with lower strengths through a layer by layer penetration test (Figure 6).

The evaluation of the risk of liquefaction has been expressed in an equation formulated by Seed and Idriss (1981). The classical method compares locally the ratio of the cyclic resistance of the soil (CRR) with the ratio of the cyclic shearing stress ratio (CSR) stemming from seismic stress. The notion of liquefaction potential is therefore linked to the fact that ratio

CRR/CSR is lower than unity. It is widely accepted that estimating the cyclic resistance ratio (CRR) can be estimated on the basis of dynamic and static penetration tests (Robertson and Wride 1998, Boulanger 2004 and Idriss, etc.).



a) b)

Figure 5. a) The breakdown into layers and density index (ID%). b) The distribution of Density Index (ID%). Test No. 1. Tailings dam No. 1.

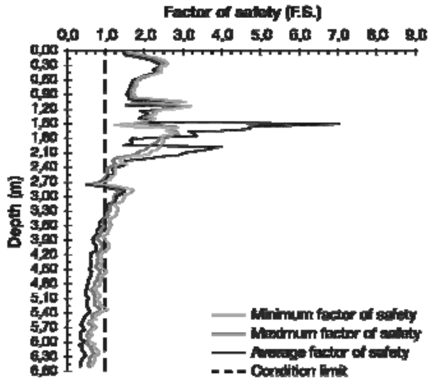


Figure 6. Example of the factor of safety (F.S) profile. Test No. 1. Tailings dam No. 1.

3 CONCLUSIONS

To predict the behaviour of mine tailings dams in view to managing the risks inherent to them, it appears necessary to carry out a probabilistic approach However, in practice implementing this type of approach is limited by the difficulty of managing the data to be used in reliability calculations for the limit conditions concerned. This article proposed a method for estimating in situ the density index (ID%) and the effective friction angle (ϕ') and its variability, making it possible to carry out a probabilistic study of these structures. A single model was proposed for all the mine tailings dams in Chile, in view to linking a probability law to ID% and the ϕ'.

A method was proposed that takes into account the spatial variability of data for performing a reliability calculation of liquefaction potential, which is the main cause for the failure of this type of structure. On the basis of the results obtained, we showed that the method proposed for estimating liquefaction potential permits evaluating the probability of triggering this phenomenon. Estimating the reliability of a dam in relation to the limit states of static and dynamic stability demonstrates the advantages and applicability of the approach, by using the variability of the geotechnical characteristics of mine tailings and resistance to penetration (qd_{N1}) in particular.

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