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CHALLENGES AND INNOVATIONS IN GEOTECHNICS

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DÉFIS ET INNOVATIONS EN GÉOTECHNIQUE

Edited by / Sous la direction de
Pierre Delage, Jacques Desrues, Roger Frank, Alain Puech, François Schlosser

VOLUME 1
Technical Committee 102

Ground Property Characterisation from In-Situ Tests

Comité technique 102

Caractérisation des propriétés des terrains par essais in situ
5.2. Parameter evaluation

The paper from Tumay et al. discusses the challenge for the effective identification of organic content in the soil based on traditional CPT and CPTU methodologies. It is very important to overcome this interpretation limitation since the cone is a popular and handy tool for subsurface investigations and soil characterization. The paper presents a comprehensive CPT/CPTU-based organic content identification method using a probabilistic soil classification system. The paper describes the probabilistic method, which employs a non-traditional modeling approach that takes the uncertainty of the correlation between soil composition and soil behavior into account. The authors affirmed that use of the compositional soil classification (U) and in-situ behavior (V) indexes for organic profiling improves the capability of determining organic material at any given depth. A detailed description of the proposed methodology and the discussion of its effective application are included in the paper.

Malabdic's paper presents the use of penetration testing devices, including the CPT and SDMT, for site characterization of a compacted earth dam. This is a case study of a small earth dam for which the remediation work was necessary given construction errors and the possible damage to the earth structure during the filling stage of the reservoir. The site investigation campaign consisted of drilling boreholes and carrying out in-situ tests (4 CPTs and 3 SDMTs) along the crest of the dam, complemented with laboratory tests. The paper focused on assessing the potential of these in-situ tests in describing physical and mechanical properties of the compacted (man-made) clay strata, since the traditional interpretation methods were developed for natural soils. The authors concluded that both CPT and SDMT clearly detected the inhomogeneous clay conditions. They also showed remarkable repeatability and proved to be valuable tools in characterizing the embankment quality, both in terms of non-homogeneity and of physical and mechanical properties.

Zabielska-Adamska & Sulewski present the use of both static (classic) and dynamic CBR methods to establish relationships between the bearing ratio and degree of compaction of fly ash. The objective was the use of the compaction degree, and also the California Bearing Ratio, as an indicator of the soil bearing capacity in compacted material. The dynamic CBR test is described in the paper, where fly ash samples were compacted by the standard and modified Proctor methods without soaking to replicate field conditions during earth structure construction. Test results indicate that both the dynamic CBR as well as the classic CBR are closely connected with the characteristics of compaction, and can therefore be used to assess the compaction of fly ash and cohesive soils. The authors suggested that the dynamic CBR test should be widely used as an alternative way to the classical method of quality control to assess the subgrade capacity of the soil.

The paper from Chapuis discusses “scale effects” in the permeability of sandy aquifers. The author’s initial hypothesis is that the large-scale tests are more likely to meet preferential flow paths, so yielding larger K values than small-scale tests, which may be viewed as some sort of scale effect. In the paper, the small scale was simulated via lab soil samples, the middle scale from field permeability tests, and the large scale with site pumping tests. The paper presents and discusses some few real case studies, observing that for all of the K distributions provided consistent images of the aquifers. It was finally concluded that scale effect was not of importance for the test interpretation in such phreatic deposits.

Mlynarek’s et al. paper discusses the interrelationship between deformation moduli from CPTU and SDMT tests in overconsolidated soils. The authors point out that glaciations in Poland overconsolidated its deep soil layers. So, it is imperative to take it into account in calculations of differential settlements of structures. The paper presents deformation characteristics estimated from CPTU and SDMT tests in clays, and focuses on a method to identify preconsolidation and to evaluate relationships between deformation moduli derived from CPTU and SDMT tools. The authors concluded that the simultaneous use of CPTU and SDMT provides a continuous picture of the changes in stiffness of heterogeneous subsoil. They emphasized the need for establishing specific calibration functions for each soil type, which may be a useful tool in the construction of a model for the subsoil’s rigidity based on $Q_0$ or $M_0$ values.

Liu’s et al. paper reports the practice and development of the piezocone test in the geotechnical engineering field of China. In this paper, the history and current development status of CPT and CPTu in China practice were systematically presented. The most used (standard) cone has the 10 cm² tip area, but both 15 and 20 cm² CPT probes are frequently used in China. The relationship between international standardized CPTu and China’s CPT is based on a large data bank of testing results related to a great number of soils. The paper presents a comparison review of the soil characterization methods in China, including the determination of stress history, deformation, consolidation and permeability characteristics.

The paper from Espinace et al. presents their 10 years of experience on the use of Panda® penetrometer to assess the stability of Chilean’s tailings dams. The authors report around 40 cases of mechanical instability from tailing dams in Chile, which were mainly due to liquefaction, slipping of banks, or settlement. The paper presents the main results that have allowed the proposition of a new methodology to control and diagnose tailing dams. It is based on in-situ determination of the geomechanical parameters (internal friction angle and density index) using the Panda® penetrometer in order to characterize the constituent materials and their variability. The authors also pointed out that this methodology allows taking into account the variability concept for stability and liquefaction risk studies when using a probabilistic approach.

Hamza & Shabien’s paper studies the compressibility parameters of Egyptian cohesive soils via piezocone tests. The major objective was to provide additional data on drained compressibility parameters, focusing on the constrained modulus ($M_c$) and on the overconsolidation ratio (OCR) for cohesive soils from geotechnical investigations at seven major sites of the Nile delta river deposit in Egypt. Enhanced propositions to estimate the OCR and $M_c$ for the studied clays are presented, allowing settlement analyses to be done with the proposed equations. The authors believe that the presented data and correlations are a valuable contribution, since it improves the current state of the art in estimating the compressibility parameters of sedimentary soils with the CPTU test.

6. FINAL REMARKS

Site characterization using in-situ testing techniques has considerably changed in the last two decades along with the rapid transformation and advances of the technology, either by the development of newer and economical electronic devices operated by laptop computers or by new mathematical and software approaches based on multi-variable, statistical or probabilistic calculations. Besides of such remarkable accomplishments, the traditional “old fashion” (past century…..) laboratory and site investigation methods are still widely in use, sometimes as the preferential or unique available method. It was clear from aforementioned review that, on the 21st century, the proper site investigation, material characterization and soil behavior prediction for the geotechnical design cannot solely rely in one isolated test technique, or on simple “local” unadjusted correlations that are probably not universally valid.

Higher sensorial levels of testing tools and combined investigation procedures are surely now available that can be
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 chilien à l'aide du pénétromètre Panda®

Espinace R., Villavicencio G., Palma J. 
Grupo de Geotecnia. Escuela de Ingeniería en Construcción. Pontificia Universidad Católica de Valparaíso, Chile. Geotecnia Ambiental, Chile.

Breul P., Bacconnet C. 
Institut Pascal – Polytech’Clermont-Ferrand. Université Blaise Pascal, Clermont-Ferrand, France.

Benz M.A., Gourvès R. 
Sol-Solution Géotechnique Réseaux, Riom, France.

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 andits application(114,903),(384,982) in the medium mining sector. It is based on in-situ determination of geomechanical parameters (internal friction angle and density index) using the Panda® lightweight 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'université 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 constitutants, 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 \( \phi \) 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 \( \phi \) 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 \( \phi \) and ID%.

2 ESTIMATION OF THE DENSITY INDEX (ID%) AND THE FRICTION ANGLE (\( \phi \))

1.1 The objective

In mine tailings with non plastic fine particles (size < 80 µm) ID% and \( \phi \) 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 \( \phi \) 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.

\[ \text{qd}_{\text{ref}} = qd \cdot C_q \]  

(1)

where: \( qd \) is the dimensionless normalised dynamic cone resistance, \( qd \) is the dynamic cone resistance, \( p_a \) is the atmospheric pressure, \( \sigma'_{\text{v}} \) 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 (\( K_s \)), 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). (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.

<table>
<thead>
<tr>
<th>Geo. Prop</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. CV</td>
<td>Av. CV</td>
<td>Av. CV</td>
<td>Av. CV</td>
</tr>
<tr>
<td>γₜ</td>
<td>3.09</td>
<td>4.6</td>
<td>3.36</td>
</tr>
<tr>
<td>Dₜₛ</td>
<td>0.13</td>
<td>19.0</td>
<td>0.11</td>
</tr>
<tr>
<td>F.C</td>
<td>28.0</td>
<td>28.7</td>
<td>33</td>
</tr>
<tr>
<td>IP</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>γₜmax</td>
<td>18.2</td>
<td>6.2</td>
<td>20.8</td>
</tr>
<tr>
<td>γₜ</td>
<td>17.5</td>
<td>6.6</td>
<td>20.1</td>
</tr>
<tr>
<td>wₜₛ</td>
<td>11.0</td>
<td>22.3</td>
<td>3.3</td>
</tr>
<tr>
<td>qd</td>
<td>4.8</td>
<td>50.6</td>
<td>2.87</td>
</tr>
<tr>
<td>Nₜₛ</td>
<td>22</td>
<td>62.5</td>
<td>12</td>
</tr>
</tbody>
</table>

γₜ: specific weight (kN/m³), Dₜₛ: median diameter (mm), F.C: percentage of fines less than 80 (µm), IP: plasticity index (%), γₜmax: Proctor dry density (kN/m³), γₜ: dry density in situ (kN/m³), wₜₛ: water content in-situ (%), qd: cone resistance PANDA test (Mpa), Nₜₛ: 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.](image)

1.3.1 Relation ID% = f (qd₁₀)

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 (qd₁₀), 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).

<table>
<thead>
<tr>
<th>qd₁₀</th>
<th>ID%</th>
<th>State of compaction</th>
<th>Mechanical behaviour</th>
<th>Liquefaction potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 17</td>
<td>0 – 15</td>
<td>Very low</td>
<td>Contractant</td>
<td>High</td>
</tr>
<tr>
<td>17 – 69</td>
<td>15 – 55</td>
<td>Low</td>
<td>Contractant</td>
<td>High</td>
</tr>
<tr>
<td>69 – 82</td>
<td>55 – 60</td>
<td>Average</td>
<td>Contractant /Limit</td>
<td>Limit</td>
</tr>
<tr>
<td>82 – 162</td>
<td>60 – 80</td>
<td>Dense</td>
<td>Dilatant</td>
<td>Null</td>
</tr>
<tr>
<td>162 – 326</td>
<td>80 – 100</td>
<td>Very dense</td>
<td>Dilatant</td>
<td>Null</td>
</tr>
</tbody>
</table>

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 (sand 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 (qd₁₀, 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 qd₁₀ by a single relation. The model used is given by the following equation:

\[ \text{ID%} = 28.5 \cdot \ln(qd_{10}) - 65.4 \quad \text{with} \quad 10.0 \leq qd_{10} \leq 326.0 \]

(2)
Replacing QC proposed by Díaz and Rodríguez-Roa (2007) was used by very close to the experimental resistance qd within one geotechnical class, it is possible to estimate since we considered that mine tailings can be globally classified for granular soils have been demonstrated experimentally and confirmed the relation between qd and qc. Their results obtained for the ratio qd/qc is equal to 1.03. More recent research performed by Rahim et al. (2004) showed by a two single relations, (2) relation qd = qcN1 is very well validated which allows using either static or dynamic penetrometers according to need.

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 Diaz and Rodriguez-Roa (2007) was used by replacing qcN1 by qdN1.

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This result is in full agreement with the works already carried out on the correlation between QC and qd obtained with a Panda peneterometer. 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 peneterometer 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 qdN1 by a two single relations,
2. relation qdN1 = qcN1 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).

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.

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 performed under stress ratio (CSR) stemming from seismic stress. The notion of liquefaction potential is therefore linked to the fact that ratio is very well validated which allows using either static or dynamic penetrometers according to need.

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

<table>
<thead>
<tr>
<th>ID%</th>
<th>Analysis of the mechanical behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av.</td>
<td>C.V</td>
</tr>
<tr>
<td>52</td>
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<td>29</td>
</tr>
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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.).

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.

Factor of safety (F.S)

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 ($\phi'$) 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 $\phi'$.

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 ($q_{u,h}$) in particular.

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