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The PANDA Technology applied to design and operation of tailings dams

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ABSTRACT

PANDA technology is currently being used to regulate compaction and provide in-depth quality control for tailings deposits in Chile, owing principally to its rapid, non-destructive, portable, easy-to-use and environmentally sustainable testing which is based on normalised methods and able to produce immediate results.

In the last few years research has been undertaken with this technology in order to define Chilean tailings deposits from a geotechnical perspective (Espinace et al., 2007; Villavicencio et al., 2011; Villavicencio et al., 2012; others) and also consider the deposit's spatial and temporal variability. To support this line of research, precedents, parameters and empirical correlations are presented here in order to determine compaction states and resistant properties which define the geotechnical behaviour of tailings dams and thickened tailings deposits in Chile.

The information presented consists of the first band of a wide range of PANDA tests carried out on Chilean tailings deposits by the 'Grupo Geotecnia de la Pontificia Universidad Católica de Valparaíso' in conjunction with the company 'Geotecnia Ambiental Ltd'. This information has been correlated with geotechnical parameters via empirical and semi-empirical methods and statistics, establishing in the process correlations to estimate resistant parameters and states, like index density (ID%), angle of friction (ϕ) and undrained shear strength (Su).

Keywords: Tailings deposits; PANDA Technology; Soil Compaction; In situ test; Tailing management

INTRODUCTION

The following is a summary of applications made using PANDA technology, (Pénétromètre Autonome Numérique Dynamique Assisté -developed in France) on several tailings deposits from Chilean mines. The adaptation of this technology has been lead by, 'El Grupo Geotecnia de la P. Universidad Católica de Valparaíso', 'El Servicio Nacional de Minería y Geología (SERNAGEOMIN), 'Blaise Pascal University' in France, the 'Geotecnia Ambiental' company and a host of other national and international institutions and companies. The results of work carried out in the name of research, development and innovation (I+D+I) concluded with the passing of norm NCh 3261 by the 'Instituto Nacional de Normalización de Chile (INN): 'Tailings deposits compaction control with lightweight dynamic penetrometer', applicable to all types of dynamic penetrometer. The applications presented here are destined for the control of the compaction of tailings deposits and for the diagnosis of their various mechanics.

PANDA METHODOLOGY IN TAILINGS DEPOSITS IN CHILE

The PANDA equipment is a variable energy lightweight dynamic penetrometer whose basic principle function is to be driven into the ground with a standard hammer (mass 2.0 kg) and with a bar mill 14 (mm) in diameter supplied with a metal cone 2 cm^2 or 4 cm^2 in diameter at its tip. The the dynamic cone resistance (qd) and the penetration achieved (e) by each strike of the hammer is registered continually using an adaptation of the Dutch formula. (Equation 1).

$$qd = \frac{1}{A_c} \times \frac{E}{e} \times \frac{M}{M + P} \tag{1}$$

The maximum depth of penetration for the control of compaction is to the order of 1.5 (m) and from 6.0 (m) to 7.0 (m) for a characterisation at depth. The maximum values for qd vary from between 20 (MPa) to 30 (MPa). (Gourvès & Richard, 1995; Gourvè & Zhou, 1997; Benz, 2009).

Applications for Compaction Control

Compared with those tools habitually employed for this function, (sand substitution and nuclear densimetre), the PANDA penetrometer offers a series of advantages which take into consideration the variability of the material in-situ, (Villavicencio, 2009) such as rapid execution, recurrence versatility, reliability of results, environmental sustainability, low cost and ease of transport. This allows for the analysis of places which are difficult to access such as the slopes of sand tailings deposits. (Espinace et al., 2007).

Compaction control is based on the comparison of the penetrometer's signal obtained in-situ with a curve which has been obtained via previous calibration in the laboratory, or in-situ with the control material to achieve a specific level of compaction and the hydrological status in particular.

Principle and Fundamental Theory

The principle theory of compaction control with PANDA penetrometer is based on the relationship that exists between the dynamic cone resistance (qd) and the dry density (γd) of the ground from the description of its microstructure and based on hypothesises derived from the micro-mechanics of granular material. (Biarez, 1977; Favre, 1980; Cambou, 1987). If the parameter to be measured in-situ is qd, according to the hypothesis of reversibility, and knowing the nature and interaction of the parameters, it is possible to determine in-depth the dry density in-situ. Research conducted by Chaigneau (2001) permitted the establishment of the relationship between qd and γd. (Equation 2).

$$\gamma d = \alpha_A \cdot \ln(qd) + \beta_B \tag{2}$$

Gourvès & Richard (1995) and Gourvès & Zhou (1997) demonstrated that the resulting penetrogramme from the penetration test carried out on homogenous granular material where density and humidity are constant, may be described in simple terms in the space log(qd)-z from the two gradients which define three characteristic parameters: the surface level resistance at the tip (qdo) the critical depth (zc) beyond which the resistance at the tip is constant, and the constant dynamic cone resistance (qd).

Calibration Methodology

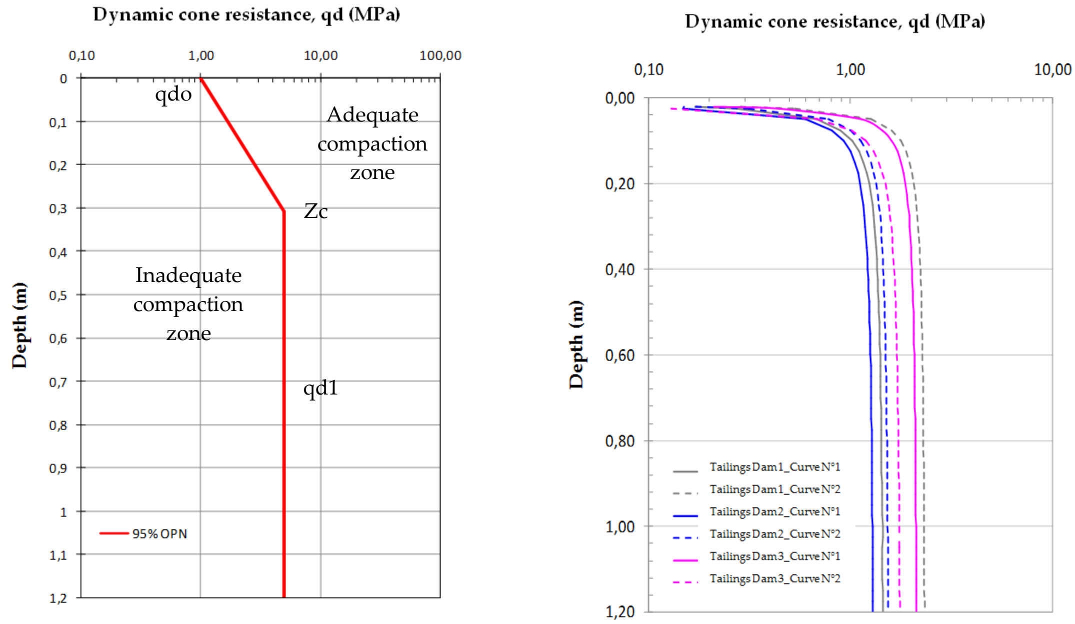
The theoretical foundation for compaction control and the correlation between the dynamic cone resistance (qd) and the dry density (γd) gave rise to calibration methodology research both in-situ and in the laboratory with the aim of obtaining control curves for different types of sand tailings deposits, taking into account the variation of its physical characteristics (granulometry), the density gradient on the interior of a compacted layer (the base layer effect) and the hydrological state in-situ at the moment of accomplishing control. The aforementioned is studied using the compaction grade habitually employed for the construction of this type of work. (Villavicencio, 2009).

The general methodology for the acquisition of **control curves in the laboratory** is based on the acquisition of parameters characterised by a penetrogramme obtained via homogeneous granular materials, corresponding to qdo, zc and qd1, obtained for a specific state of compaction and humidity. (Chaigneau, 2001) In a series of PANDA tests undertaken on the interior of a normalised calibration mould, (NCh 3261) the average value of said parameters is calculated, taking into account a particular hydrological state (dry, medium, humid) and five levels of compaction relating to the Proctor value. The variation of each parameter is clearly described via a type of logorhythmic function. (Chaigneau, 2001) For a dry density value (γd) associated with a compaction scale (OPN%, OPM%) and a particular moisture state, the parameters qdo, qd1 and zc, which define the compaction control curve, may be obtained. (See figure 1a).

Calibration in-situ is based on the acquisition of a PANDA compaction control curve for one type of tailing of a pre-determined humidity and compaction grade (depending on the number of rounds and the thickness of the layer). To this end, calibration spaces are constructed whose dimensions are defined depending on the machinery used in the compaction process and on the surface discharge of the tailings sand.

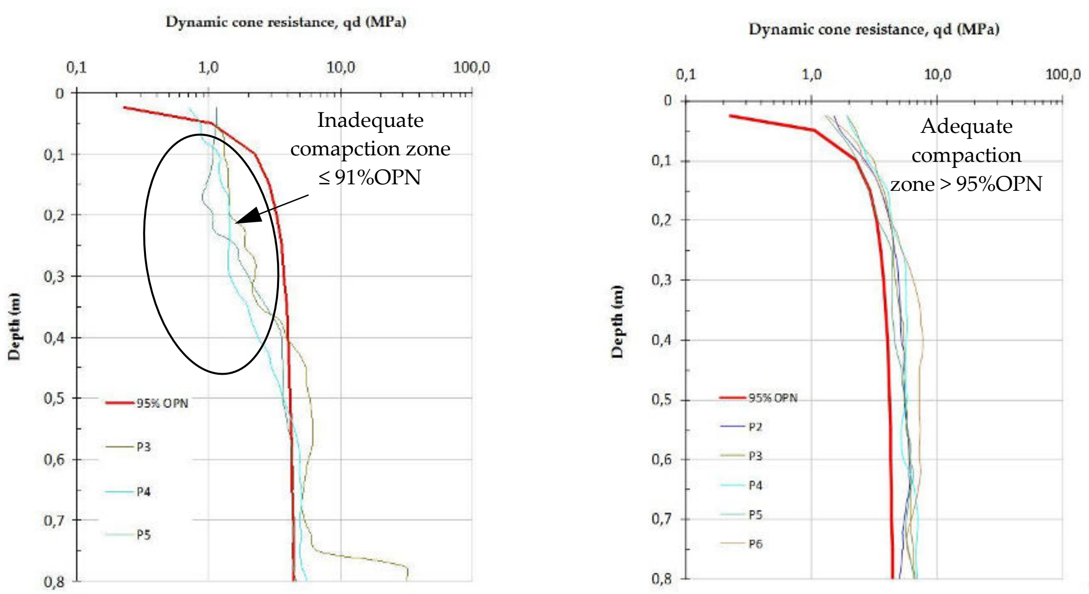
Control points are established along the longitudinal axis where PANDA tests are carried out and samples are extracted for later characterisation in the laboratory. The calibration process is repeated if the characteristics of the sand tailings or the compaction machinery vary. The control curve associated with sand tailings, the humidity in-situ, the compaction grade and the thickness of the deposit layer is obtained through a simple regression analysis. Figure 1b shows the control curves for three tailings deposits with this methodology.

Figure 2 summarises the experience of a Chilean tailings deposit in which sand cone and nuclear dens metre tests have been carried out to determine the compaction grade in-situ of the tailings deposits with reference to the normal Proctor test. A sector was compacted to 91% OPN and the corresponding PANDA penetrogrammes are observed to the left of the control curve in the inadequate compaction zone. (Figure 2a) The other sector corresponds to a compacted zone (≥ 95% OPN) in which the penetrometric signals are found to the right of the compaction control curve where compaction is adequate.



a) b)

Figure 1 a) Laboratory Calibration, with 95% OPN and medium moisture state. b) Calibration in-situ, with 95% OPN for different sands and moisture states



a) b)

Figure 2 Compaction control. PANDA penetrometre. a) Sector 1. b) Sector 2

Applications for characterisation at depth

For this characterisation, the test requires cone section of 4.0 cm^2 necessary for measuring only the dynamic cone resistance (qd), eliminating the shaft caused by lateral friction between the ground and the bar. Prospecting at depth through qd, measured within the maximum recognised depth (6.0 m to 7.0 m) allows an estimate of geotechnical parameters in-situ, the thickness of the layers and the reconstitution of the internal structure of the tailings deposit at a compaction grade depending on the index density (ID%).

Correlations to estimate geotechnical parameters through qd

In order to estimate geotechnical parameters in tailings deposits from PANDA tests, semi-empirical correlations are used. Research by Villavicencio (2009) and Villavicencio et al (2011) through laboratory calibration tests compiled and correlated the dynamic resistance corrected by the pressure of confinement (Salgado et al., 1997) and normalised to atmospheric pressure (qd_{N1}) with parameters like the state of compactness (expressed as ID%) and with the angle of friction (ϕ). (Figure 3).

$$qd_{N1} = qd \cdot C_q \quad \text{with} \quad C_q = \left(p_a / \sigma'_v\right)^c \tag{3}$$

$$ID\% = 28.5 \cdot \ln\left(qd_{N1}\right) - 65.4 \quad \text{with} \quad 20.0 \le qd_{N1} \le 326.0 \tag{4}$$

$$\phi = 14.79 + 5.54 \cdot \ln\left(qd_{N1}\right) \quad \text{with} \quad 20.0 \le qd_{N1} \le 280.0 \tag{5}$$

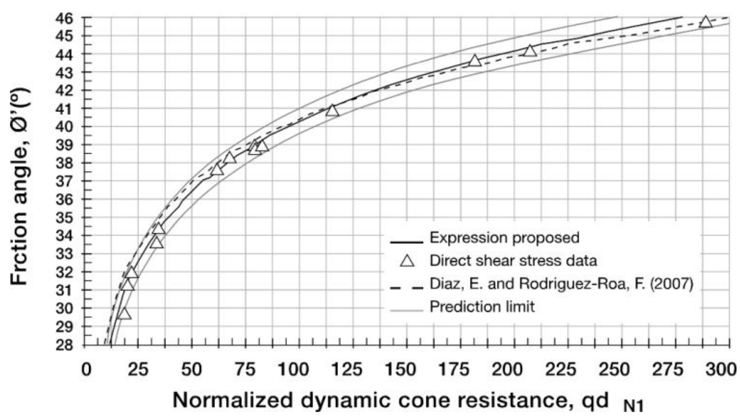


Figura 3 Experimental points, proposed and bibliographic relations for estimating the effective friction angle (ϕ’) of mine tailings as a function of the qd_{N1} (Villavicencio et al., 2011)

For depths of up to 7.0 m, Villavicencio proposes connecting the resistance qd with the standard penetration index (N_{SPT}) or the pseudo-static resistance tip (qc). Taking into account research carried out by these authors, precedents obtained from Chilean experiences of the mechanical behaviour of tailings deposits resulting from the application of important seismic solicitations, criteria currently used in Chile by engineering consultants for the design and geotechnical control in tailings deposits, and the results obtained from dynamic PANDA penetration tests and SPT, an initial classification has been proposed which will require continual analysis in the future. (Table 1) This information enables the rapid and economic estimation of liquefaction tests in tailings deposits in stages of operation and post closure.

Table 1 Correlations to estimate the liquefaction potential in tailings deposits

qd_{N1} (Mpa)	$(N_1)_{60}$	ID%	State of compaction	Mechanical behaviour	Liquefaction potential
< 20	< 8	< 20	Very low	Contractant	Very high
20 - 48	8 - 15	20 - 45	Low	Contractant	High
48 - 57	15 - 20	45 - 50	Compacted	Contractant	Equilibrium
57 - 81	20 - 30	50 - 65	Compacted to dense	Limit	Low
81 - 193	30 - 50	65 - 85	Dense	Dilatant	Very Low
>193	>50	85 - 100	Very dense	Dilatant	Null

APPLICATION OF PANDA TECHNOLOGY IN TAILINGS DEPOSITS

Applications in reservoir and sand tailings deposits

An extensive database of PANDA tests on the characterisation of tailings deposits, their mineralogical information and a knowledge of the type of operation carried out on various tailings deposits in Chile has determined a preliminary band characteristic of an empirical nature which allows for the identification of the compaction quality of sand deposits from the penetrometre signal of PANDA tests. Figure 4 shows the band estimate for certain penetrometer signals from Chilean reservoir tailings obtained be Geotecnia Ambiental ltd.

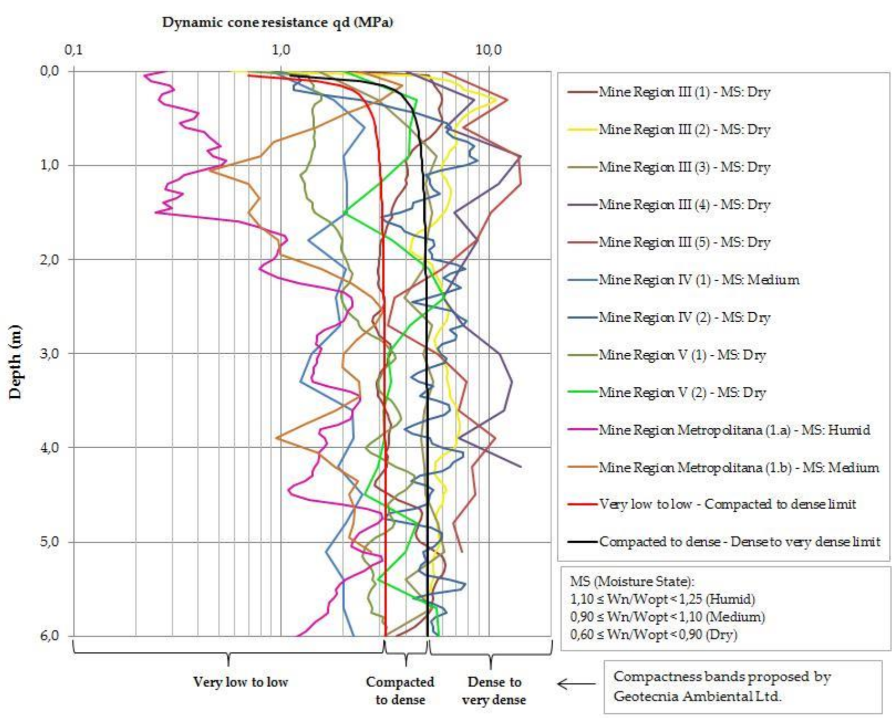


Figure 4 Empirical band of compaction states and some PANDA signals from Chilean reservoir tailings. Source: Geotecnia Ambiental Ltd.

It can be concluded that a resistance at the tip (qd) of 3.0 MPa to 5.0 MPa is equivalent to a qd_{N1} between 75 MPa to 109 MPa for hydrological states from dry to medium, with an ID% from 63% to 73% respectively.

Applications on thickened tailings deposits

The application of the system of depositing thickened or paste deposits in Chile is found in an initial phase, mainly in the deposits of large mines. This new technology requires the performing of laboratory tests and pilot scale checks to predict the behaviour of thickened tailings with greater certainty and above all to determine the risk of liquefaction or settling amongst other geotechnical analysis. The execution of such tests requires special attention in its implementation in order to be able to verify models and achieve reliable extrapolations. Amongst other requirements, the rheology of the tailing (represented by the yield stress) is key in obtaining a precedent like the beach gradient for each deposit. In addition they are parameters like post-liquefaction resistance or final un-drained resistance, Su, or the deformability of thickened tailings.

Geotecnia Ambiental has performed a series of tests in-situ to characterise thickened tailings deposits, using the PANDA penetrometer and the vane test. In the case of tests on tailings with fine contents between 50% and 70%, dry density between 1.45 t/m^3 and 1.65 t/m^3 and saturation grades higher than 75%, it is necessary to determine the residual undrained shear post liquefaction (Su) which depends as much on the densification state as the vertical tension effect, σ'_v . For this the empirical expression Su/σ'_v is used constant with a minimum Su value close to 10 KPa obtained from the correlation of the two mentioned tests. One is able to check that when the tailing loses its saturation condition and it is found partially saturated, the un-drained resistance for the same case analysed rises above 50 KPa.

Regarding the determination of deformability parameters, PANDA tests performed on thickened tailings deposits show an increase in the dynamic cone resistance (qd) up to 7.0 m deep with a linear or bilinear relationship in the semi-log graphic. For a studied case, it can be deduced that the tip resistance could be of the kind $qd = 3z^{0.7}$ (z in m and qd in kg/cm^2). Studies carried out by Chaigneau (2001) and employed by those authors, relate the resistance at tip penetration of the CPT (qc) with the PANDA test qd, via the relationship qd PANDA = 0.98 to 1.03 qc. Taking into account several sand studies which have proposed correlations between the Determination Module (E) and the resistance at the tip, qc, for sand tailings or other material with similar low plasticity behaviour, the use of the relationship E/qc = 3.5 is proposed. Through this it is possible to estimate Elastic Modulus (E) at depth as $E=10z^{0.7}$ (where z in m and E in kg/cm^2). In addition PANDA technology is being successfully used in the operation control of thickened tailings deposits to determine layer thickness, compaction levels or resistance at depth.

CONCLUSION

Several applications performed on sand reservoir tailings and on thickened tailings deposits in Chile by in-situ test technology via the dynamic portable penetrometer PANDA have been presented in this article. It has been proven that this tool is very valuable as much for its design as for the operation control of deposits as it permits the rapid introduction of modifying actions in this last stage when deviations are detected in the project.

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NOMENCLATURE

Ac	PANDA tip area
c	normalisation coefficient (0.5 to 0.75)
e	penetration of the PANDA tip into the ground with every hammer strike.
(E)	deformation Module
E	PANDA energy applied
M	PANDA hammer mass
P	bar mill and PANDA head mass
pa	atmospheric pressure (1 atm ≈ 100 KPa)
qd	dynamic cone resistance
σ'_v	vertical stress effect
Su	undrained shear strength
γd	dry density of the tailings dam

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