Geotechnical characterisation of tailing deposits with instrumented variable energy dynamic penetrometer: a state of art

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ABSTRACT

Chile is the third country with most tailing dams worldwide (764, of which 15% active, 62% inactive, and 23% abandoned). Today, one of the main challenges of the mining industry is to ensure environmental sustainability. To achieve this, it is not only necessary to have regulations guaranteeing correct design, maintenance, closure stages, but also supervision and suitable technology enabling rapid, reliable, and cost-effective diagnosis of the overall tailings dam stability. For the last 20 years, French instrumented dynamic cone penetrometer, P.A.N.D.A®, has been used for in-depth quality control of tailings deposits, mainly due to its rapidity, portability, easy-to-use, cost-effective, and environmentally friendly testing which is based on standardized methods and able to produce immediate results. The last few years, different studies have been carried out to characterize tailings dams from a geotechnical perspective as well as to assess their spatial and temporal variability. This article presents a summary of the 20 years of Chilean experience in compaction quality control and geotechnical characterization of mine waste facilities using P.A.N.D.A® to assess the overall stability, slope analysis stability, liquefaction triggering, spatial variability of material properties and evaluation of some geotechnical parameters. Indeed, given the scale of the problem these structures represent for the community and the environment, it seemed necessary to bring together most of the work carried out in Chile to propose an innovative alternative to the rest of the mining community.

Keywords: Tailings Dams, instrumented DCP, Compaction control, Liquefaction.

1. Introduction

Chile, being the world's leading copper producer, faces the significant challenge of ensuring the physical integrity of its tailings deposits or liabilities, where desired resources extraction from mining activities add up to just 1% of the final result, alongside a large generation of contaminating waste (Statista 2023). Currently, the country ranks third worldwide with the most tailing dams having 764 in total, with 15% classified as active, 62% as inactive, and 23% as abandoned. Since the early 20th century, more than 40 cases of mechanical instability regarding tailing dams have been reported, primarily attributed to liquefaction, flow event erosion, and overtopping.

Historically in this country, tailings dams have been the most widely used technology for storing tailings. This is why the Chilean legislation, based on the (D.S N°248 2007), defines the different types of tailings deposits authorized to be contained, with the operation or construction process being crucial to ensure the physical stability of said deposits.

Nowadays, environmental sustainability also presents itself as a main topic and required procedure in the mining industry, meaning not only the creation of regulations for correct design practices, maintenance, closing stage of operations, and so on, but also effective supervision with suitable technology that could provide better, reliable, cost effective and rapid diagnosis of the tailing dams overall stability. In recent years, we have witnessed disasters involving tailings dams that evidence the risks these facilities pose to both the community and the environment.

Since the beginning of the 20th century, around 40 cases of mechanical instability have been recorded, generated by liquefaction phenomena, slope instability and seismically induced deformations, causing human, economic and environmental losses (SERNAGEOMIN 2018). Therefore, compaction controls are crucial to manage the construction process to not only measure the degree of surface compaction through conventional tests, such as the nuclear densimeter and sand cone, but also measure the layer thickness and variability. It is for this reason that the (NCh 3261 2012) is published, oriented to the compaction control in the operation or construction phase of the tailings deposit, which also proposes the P.A.N.D.A® equipment as a reference test (Gourvès, 1991), allowing for the measure of layer thickness, degree of compaction, and variability of the material at a lower cost than the classic procedures.

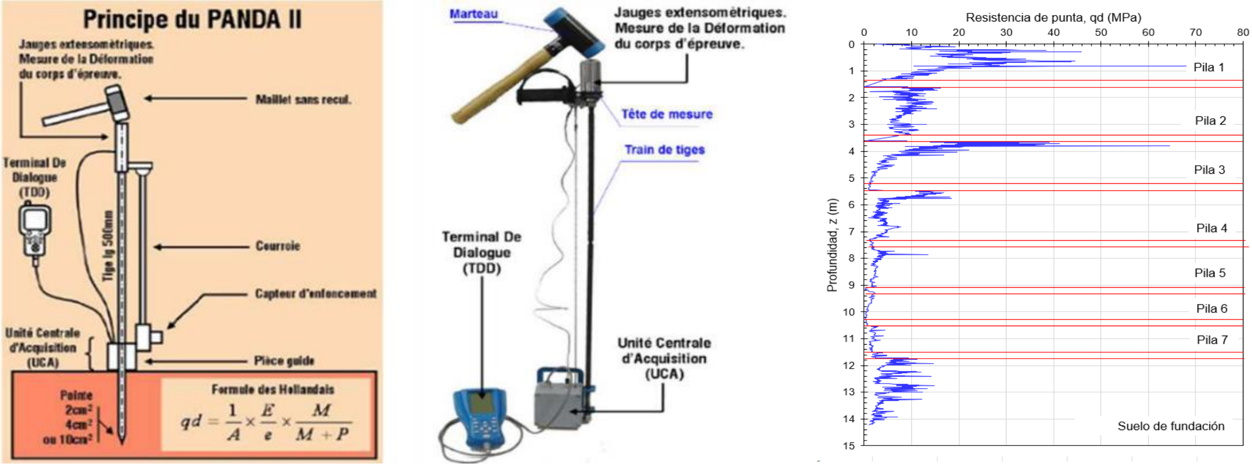


Figure 1. Equipment components of the P.A.N.D.A® General principle of measurement, components and penetrogram (log(qd)) as a function of depth obtained during a characterization borehole of a gravel leached pile in Chile.

The implementation of this test has made it possible to obtain strength and geotechnical parameters specific to the mining waste, as well as correlations with other classic geotechnical tests such as MASW, SPT and CPT. The main applications of the P.A.N.D.A® tests in different types of tailings deposits and correlations of parameters with other geotechnical equipment obtained in mining in Chile are presented below, as well as other approaches to reduce uncertainty, discussed further in this paper.

1.1. P.A.N.D.A test

The P.A.N.D.A test consist of a light dynamic penetrometer of variable energy, whose basic objective is to dive into the ground through the impact of a standard mass hammer (2.0 kg) to the anvil connected to a train of bars of 14 (mm) in diameter, which at the other end has a conical tip of 2.0 (cm2) in diameter. When the anvil is struck, it generates vibrations that are recorded by the acquisition center (UCA), registering the dynamic penetration (qd) obtained from the ground just after the strike, and then sending this information to the dialogue terminal (TDD), Fig.1 shows the elements of the equipment. The information recorded by UCA allows for automatic calculations of the qd value through the Dutch formula, being also automatically recorded in the system's memory and plotting these values as a function of depth (z), which is subsequently analyzed by the WebSprint® software, generating the Log of qd(z) curves, shown in Fig.1, called penetrograms.

1.2. Application of P.A.N.D.A in tailings dams

This equipment has been used in various kinds of tailings deposits regarding Chilean mining, including tailings dams and thickened deposits, as well as in other forms of mining waste associated with leaching tailings. Its application covers both operational and post-construction controls, with the purpose of estimating the resistance in depth, degree of compaction, variability, and layer thickness. It has been also used to determine geotechnical parameters, such as correlations between tests, liquefaction potential, friction angle and liquidity index.

The main results of the studies carried out on tailings deposits during the last 20 years are presented below.

1.3. Compaction control with P.A.N.D.A

The principle of compaction control using the P.A.N.D.A®. equipment is based on the cone resistance qd, which depends on the properties of the soil as a function of its resistance to penetration. Different researchers have shown a relationship between the dry density, γ_d, of a material and qd. (Chaigneau 2001), established a connection between these parameters using the P.A.N.D.A® test. Based on their study, they concluded that qd and γ_d are directly proportional; the more γ_d, increases, so will qd increase, delivering Eq. (1) which corresponds to a logarithmic function containing regression coefficients A, B and C that depend on the type of soil obtained by laboratory calibration.

$$\gamma_d = A(w) + B\ln(qd) + C \; (1)$$

where γ_d is the dry density, w the moisture content and qd corresponds to the average tip resistance. Parameters A, B and C of a soil type relate w with qd, obtaining a "calibration curve", being determined from it the values of qdR and qdL for the density γ_d (which for example represents 95% of the density of the normal or modified proctor).

1.3.1. Compaction controls and determination of layer thickness at conventional tailings dams

As previously mentioned, (NCh 3261 2012) is used in Chile for compaction controls in the operation or construction phase of tailings deposits.

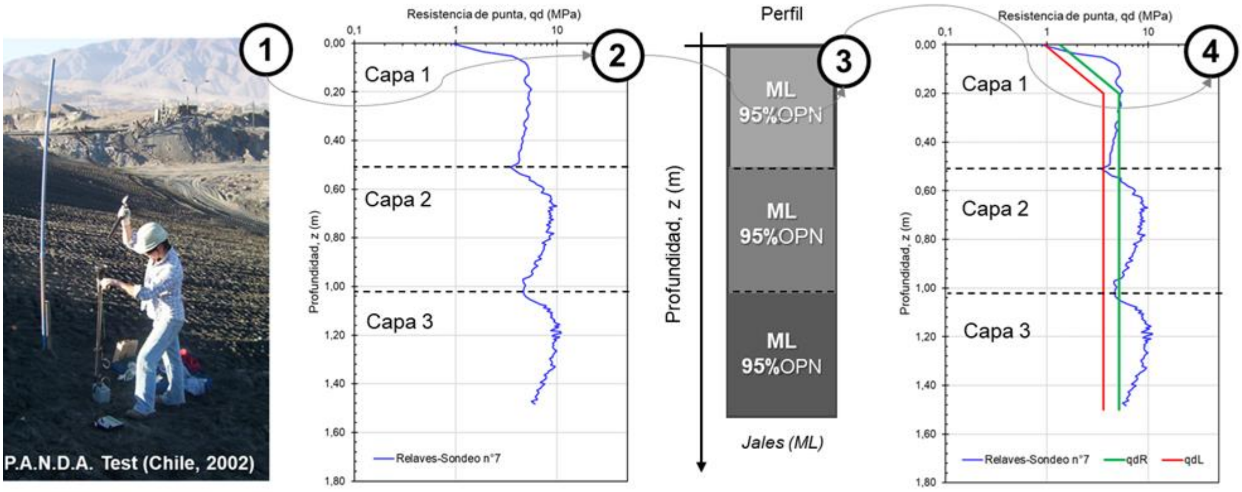


Figure 2. General principle for compaction control with P.AN.D.A® (NF P 94-105 and Nch 3261-12) (a) carrying out the in-situ control test, (b) obtaining the control penetrogram, (c) construction of the profile to be controlled (thickness, soil type and compaction quality) and (c) verification of thicknesses and comparison with the reference curves qdR and qdL. for the case of a tailings deposit (copper) in Chile.

It generates reference curves (qdL y qdR) with the objective of controlling a reference density, which is set at 95% of the optimum density of the modified Proctor (OPM). These curves are obtained through laboratory calibration, as illustrated in Fig. 2, enabling the identification of resistance in depth in terms of qd, and the determination of its thickness through the penetrograms.

The limit curves (qdL) and reference value of dynamic cone resistance (qdR) are obtained by laboratory calibration, following five steps:

a) Determination of the particle size distribution of the material, density of solid particles and maximum density by standard proctor.

b) Preparation of five test specimens, using a test mold, each one of them compacted with a different compaction energy (ranging from 80 a 110%), considering three hydric states for each specimen. Three P.A.N.D.A® tests for each specimen must be performed.

c) Determination of dry density using the sand cone method and calculation of the moisture percentage

d) Determination of penetrometric parameters q_{d0}, Z_c y q_{dL}.

e) Analysis and processing of the information.

1.3.2. Compaction controls considering material and structure variability.

(G. Villavicencio et al. 2012) proposes a methodology to determine, in-situ, the degree of compaction in depth and layer thickness of the deposit, considering the variability of the material and structure of the tailing's dams, an aspect that is not currently considered by Chilean engineering.

Tailings sands present two types of variability, namely material and structural, that can be analyzed on two types of scales: spatial and temporal. The spatial scale is associated with the dispersion of the geotechnical characteristics of the tailings sand and structure in space. On the other hand, for the temporal scale, the variability is related to the aging effect of the type of material, produced by the cementation of the particles, change of water status and other factors (G. Villavicencio 2009).

The in-situ calibration is based on compaction control curves, for a specific material, considering the moisture and degree of compaction. These parameters are a function of the number of passes and layer thickness. By means of calibration fields, whose dimensions are defined by the compaction machine used, 5 test points are established along the longitudinal axis. These points are constituted by P.A.N.D.A ®, sand cone and sample extraction, to evaluate the Proctor, granulometry and density of solid particles.

This generates the creation of the control curves associated with tailings sand through a simple linear regression that takes into consideration the in-situ moisture, degree of compaction and layer thickness shown in Fig. 3.

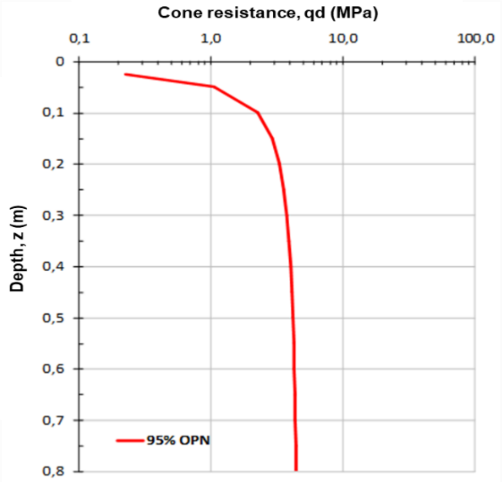


Figure 3. Calibration curve for compaction control

The P.A.N.D.A ® equipment allows also for the estimation of the variability of compacted tailings layers. Its speed makes it possible to obtain many surface and depth tests of the degree of compaction of one or several layers, obtaining in addition a spatial representation of the depth of the test measurement.

To gather said representation, interpolation techniques are considered as the inverse of the anisotropic distance, making it possible to visualize the tip resistance qd and its spatial structure, and to identify zones of diverse resistance and behavior.

1.3.3. Liquefaction potencial control

Based on the work of (Espinace, Villavicencio, and Lemus 2013), there are some proposed values of qdn1 based indices that define the states of compactness, mechanical behavior and liquefaction potential.

This work is built on the empirical correlations of (G. Villavicencio 2009) and (A. G. Villavicencio et al. 2011), who also propose a normalization of the parameter qd as a function of confining pressure, generating Eq.2 which provides information on the compactness state (ID%) and friction angle (φ), through Eq.(3) and Eq.(4).

$$qd_{N1} = C_q * qd \; with \; C_q = \left(\frac{p_a}{\sigma_v'}\right)^c \tag{2}$$

where qd_{N1} corresponds to q_d corrected for confining pressure, C_q the normalization coefficient and c the normalization exponent obtained from other studies of (A. G. Villavicencio et al. 2011), which describes that, due to the nature and variability of compaction in in-situ mine tailings, this exponent can take values between 0.5 to 0.75.

$$ID\% = 28.5 * ln(qd_{N1}) - 65.4 \tag{3}$$

Where ID% corresponds to the compactness state, as a function of qd_{N1}, valid for the range between 20 and 326 mpa.

$$\varphi = 14.79 + 5.54 * ln(qd_{N1}) \tag{4}$$

Where φ corresponds to the effective friction angle of mine tailings as a function of qd_{N1}, valid for the range between 20 and 280.

Said work puts forward the indexes shown in Table 1, which was constructed through P.A.N.D.A ® and SPT tests, coming from tests carried out in several tailings dams in Chile.

Table 1. Liquefaction assessment indices for tailings dams.

qdn1 [Mpa]	**(N1)60**	**ID %**	**State of compactation**	**Mechchanical behaviour**	**Liquefaction potential**
<20	<8	< 20	Very low	Contractant	Very high
20 – 48	8 – 15	20 – 45	Low	Contractant	Equilibrium
48 – 57	15 – 20	45 -50	Compacted	Contractant	Low
57 – 81	20 – 30	50 – 65	Compacted to dense	Limit	Very low
81 – 193	30 – 50	65 – 85	Dense	Dilatant	Null
> 193	>50	85 - 100	Very dense	Dilatant	

The values shown in Table 1 are validated for qd values in the range of 3 to 5 Mpa, being equivalent to qd_{N1} between 75 and 109 Mpa, and applied for dry to medium water conditions, with an ID% between 63 and 73%. Furthermore (G. Villavicencio et al. 2016) considers the work by (Espinace, Villavicencio, and Lemus 2013), defining the variability of the relative density (ID%) as an estimation of a depth function, and thus evaluating the contractive or dilatant behavior and qualitatively associating the liquefaction potential. In addition, the classical method of (Seed and Idriss 1981) is considered. This consist of the ratio between the cyclic soil resistance (CRR) and the cyclic stress ratio (CRS) derived from the seismic stress, where he proposes to obtain the CRR coefficient by P.A.N.D.A®, using Eq. (2). Said parameter must be taken to an equivalent value of clean sands -when the tailings sand has more than 5% fines in content- $(qd_{N1})_{cs}$. Using correction factors linked to the percentage of fines (Kc). Where Eq. (5) is proposed for values $(qd_{N1})_{cs} < 50$ and Eq. (6) for values $50 \leq (qd_{N1})_{cs} \leq 160$ which allows obtaining the CRR as a function of $(qd_{N1})_{cs}$.

$$\mathrm{CRR}_{\sigma=1,\ \alpha=0} = 0.833 * \left[\frac{(qd_{N1})_{cs}}{1000}\right] + 0.05 \tag{5}$$

$$\mathrm{CRR}_{\sigma=1,\ \alpha=0} = 93 * \left[\frac{(qd_{N1})\mathrm{cs}}{1000}\right]^3 + 0.08 \tag{6}$$

Where σ is the vertical stress and α the static shear stress. Eq. (7) is proposed in order to obtain the parameter Ic (index of soil behavior type) as a function of the percentage of fines (FC), due to the invariance of the tailings material, since this value is a function of Kc.

$$Ic = 1.32 + 0.14\sqrt{FC\%} \tag{7}$$

This also creates Eq. (8) which allows to obtain CRR, ξR as a function of ID, describing the relative state of the material and its mechanical behavior at different relative densities.

$$\xi R = \frac{1}{Q - ln\left(\frac{100(1+2k_0)\sigma' v}{3p_a}\right)} - ID \tag{8}$$

where ξR= relative state index; Q=empirical constant of mineralogy and particle fracture potential (sand tailings, Q=9); k_0= lateral pressure coefficient; $\sigma' v$= vertical effective stress (atm); p_a = atmospheric pressure (1.0 atm); ID= relative density.

1.4. Control process for thickened tailings deposits

Based on the study of (Espinace, Villavicencio, and Torrejón 2016), P.A.N.D.A® test can identify the layers state allowing to define the necessary deposition time of the successive layers and to estimate, in the operational phase, the risk of liquefaction in superficial zones. It also proposes a methodology to obtain the compaction control and the identification of geotechnical parameters, considering the peak strength qd [Mpa], which is related to the in-situ condition test of the different tailings layers and obtaining its strength. It describes that qd is related to the water status. A soil is highly liquefiable if the plasticity index (PI) is less than or equal to 12 and moisture ratio w/LL greater than or equal to 0.80 are applied.

It is also pointed out that another parameter of interest for this type of deposit is the liquidity index (IL), which represents the state of the medium. IL can be obtained through Eq. (9) and Eq. (10), while Eq. (11) allows to obtain w%.

$$IL = 1.42 - 0.272 * qd \qquad (9)$$
$$IL = -3.095 + 4.074 * (W/LL) \qquad (10)$$
$$w\% = 1/(0.038 + 0.004 * qd) \qquad (11)$$

Where IL corresponds to the liquidity index, qd to the tip resistance in Mpa, w to the moisture ratio and LL to the liquid limit. From Eq. (5), Eq. (6) and Eq. (7), a certain range of values can be determined to estimate the liquefaction potential during the operational phase which are shown in Table 2.

Table 2. Indices for evaluating liquefaction potential for a thickening tailing with qd.

qd [Mpa]	**Humidity, w %**	**Liquidity ratio, IL**	**State**	**Liquefaction potential**
<1	> 24.0	> 1.0	Liquid	Very high
1.0 – 2.0	20.0 – 24.0	0.0 – 1.0	Plastic	High
2.0 – 4.0	18.0 – 20.0	0.0 - 1.0	Plastic	Medium
4.0 – 5.0	16.0 – 18.0	<0.0	Semi-solid	Low
> 5	< 16.0	<0.0	Solid	Very Low to null

1.5. Application in post construction control

(D.S N°248 2007) is the regulation in charge of approving mining tailings deposition projects in Chile, establishing standards to guarantee the welfare of people and goods. It indicates approval procedures, as well as construction and closure requirements. One of these important parameters to control is the liquefaction that can be produced in the resistant walls of the tailings dam. The key factors to reduce or prevent liquefaction are grain size distribution control and the degree of compaction.

In the case of deposits that were not controlled in their construction due to the time they were implemented, depth resistance, layer thickness and variability need to be known. (A. G. Villavicencio et al. 2011) mentions that the variability of the tailings sands and tailings deposit resistance is influenced by the construction method, layer thickness and mineralogical origin. Likewise, he describes that when the material loses moisture it increases its resistance parameters over time, but this does intel that the deposit is safe.

1.5.1. Application to inactive tailings impoundments

As previously mentioned, there have been around 40 cases of failures in tailings dams (TD), constructed by aforementioned method in medium size mining companies, caused either by seismic liquefaction, slope instability and/or overflow. The main factors of physical instability (EF) in TDs include inadequate design, poor construction process and operation, even with proposals like Sernageomin with a methodology to assess the EF of mining facilities (SERNAGEOMIN 2018), its implementation is hampered by the lack of detailed TD information from companies.

In this context, the methodology proposed by (A. G. Villavicencio et al. 2024) becomes important. It consists of the use of cost-effective exploration tools (UAV topographic survey, P.A.N.D.A ® penetrometer, DCPT dynamic cone penetration test and MASW and MAM geophysical tests), allowing for the generation of 2D and 3D geometric/geotechnical models using interpolation methods such as inverse distance weighted (IDW). This enables the reconstruction of existing old tailings dams, identifying areas that require specific studies when the EF is deficient (e.g. seismic liquefaction, slope instability, etc).

This methodology has three stages; i) generation of digital elevation model (DEM), considering the location of geotechnical and geophysical tests, and classical topography (GNSS and total station) to generate DEM; ii) generation of stratigraphic models for the deposit and geotechnical logs to have closer approximations to the constituent layers of the embankment and identify the depth of the foundation soil; iii) generation of a 3D geometric/geotechnical model and identification of critical areas for physical stability.

This methodology of the TD, located in the metropolitan region of Chile, was built by 20th century methods: ascending of embankment construction with cyclone sand mats and/or use of full flow by drying of the material (Dobry and Alvarez 1967).

The geotechnical tests were distributed in areas affected by liquefaction and apparently stable areas with higher elevations and significant slope gradients, validated by TD field experts. The use of the cost-effective assays and historical information from the mining company that owns the TD is used to generate the DEM model obtained for TD that considers slopes, heights, volumes, surfaces (liquefied and non-liquefied zones) and location of the geotechnical tests.

This approach generates a model of the foundation soil using the IDW technique, as shown in Fig.4.

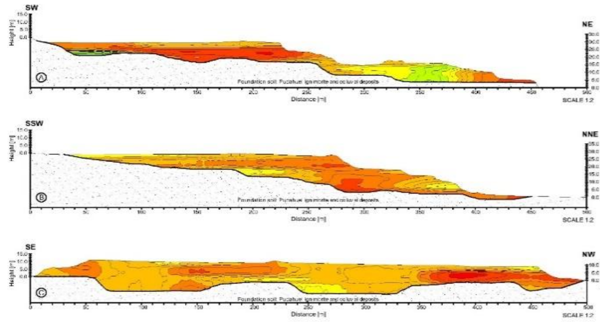
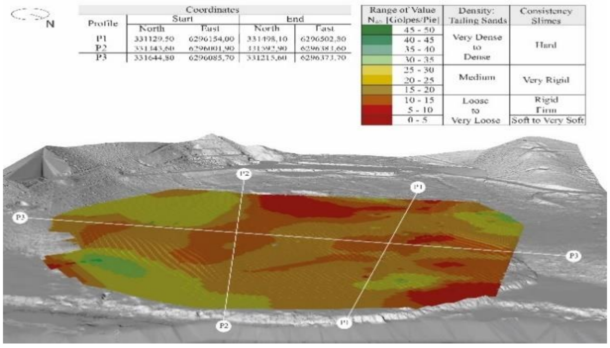


Figure 4. Foundation soil model

After estimating the foundation soil, the states of in-situ compactness in non-cohesive soils or consistency in fine soils are defined as a function of the corrected standard penetration resistance index N60 (corrected field NSPT value; average hammer energy ratio of 60%, rod length, type of soil samplers and drill hole diameter), this parameter being obtained through correlations from other sources of information; NDCPT and qd.

Said approach allows to spatialize and validate the in-situ state (compactness or consistency) of tailings and foundation soil through shear wave velocity ranges Vs, as follows: Vs > 350 m/s, foundation soil; Vs: 350 - 180 m/s, tailings sands; and <180 m/s, tailings sands or muds.

Thus, it is possible to identify zones in the TD as shown in Fig.5 with different EF conditions, based on the in-situ state of the tailings correlated with the N60 parameter.



Profile	Coordinates			
	Start		End	
	North	East	North	East
P1	331129,50	6296154,00	331498,10	6296502,30
P2	331343,60	6296001,90	331392,90	6296381,60
P3	331644,30	6296085,70	331215,60	6296373,70

	Range of Value N_{60} [Golpes/Pie]	Density: Tailing Sands	Consistency Slimes
🟩	45 - 50	Very Dense to Dense	Hard
🟩	40 - 45		
🟩	35 - 40		
🟩	30 - 35		
🟨	25 - 30	Medium	Very Rigid
🟨	20 - 25		
🟫	15 - 20		
🟧	10 - 15	Loose to Very Loose	Rigid Firm
🟥	5 - 10		
🟥	0 - 5		Soft to Very Soft

Figure 5. Model N60 of the tank.

1.6. Application to other types of mining waste

The methodology proposed by (Fourie et al. 2021) addresses the evaluation of the physical stability (EF) of tailings deposits generated by copper leaching processes. Being Chile a seismic country, it is crucial to evaluate long-term EF during the closure and post-closure phase. This methodology is implemented from the initial stage of the project and takes into account key factors, estimation of on-site conditions, and appropriate calculation methods.

It was developed in a leach waste dump (LWD), located in the north of Chile, projected to store 12 million m^3 of stepped geometric configuration with benches and berms up to a maximum height of 65 m, which can be seen in Fig. 6. LWD are geotechnically complex materials with broad physical and chemical characteristics, generally understood as gravels, sands and clays of low plasticity (GC-SC, SC or GC). They are deposited when they reach a moisture content of 15% or less by drying them at room temperature and distributed by excavators to then be compacted by construction machines.

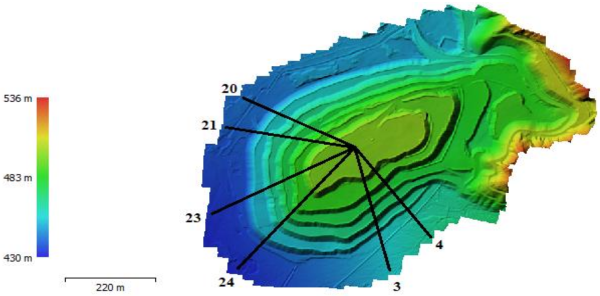


Figure 6. DEM Model LWD

In order to implement this methodology, the following must be considered:

1. Geotechnical characterization of leached tailings at depth, knowing that the average mining sector are usually controlled superficially using classical tests such as sand cone, sample extraction and to some extent penetrometer tests.
2. Identification and analysis of the morphology of the study site, in terms of geometry (slopes and heights) and in-situ conditions, in order to identify instability mechanisms.
3. Obtaining cost-effective geotechnical parameters (UVA imaging, geotechnical and geophysical testing).
4. Evaluating the EF of the deposit in the closure stage.

The cost-effective tests used for this study are P.A.N.D.A ®, MASW and MAM, and spectral H/V ratio.

To seismically classify the soil, shear waves (Vs) and other tests are considered. According to (Fourie et al. 2021), the Nakamura test is used in Chile to estimate the pre-dynamic period. This test considers the environmental vibrations and the HVSR spectral ratio to obtain the nakumara period (Tnak).

The relationship between Vs and Tnak allows to define the in-situ state of the deposit, identifying hardness of the reservoir foundation.i) Vs ≤ 180m/s (medium consistency soils); ii) 180m/s ≥ Vs > 350m/s and Tnak < 0. 75s (medium dense or medium firm soils); iii) 350m/s ≥ Vs > 500m/s and Tnak < 0.4s or flat HVSR (dense or firm soils); 500 ≥ Vs > 900m/s and Tnak < 0.3s or flat HVSR (soft or fractured soils, very dense soils); Vs > 900m/s and Tnak < 0.15s or flat HVSR (rocky or cemented soils). Eq. (12) estimates depth based on the parameters Vs (Vs_{LWD}) and Tnak.

$$T = \frac{4 \cdot H}{Vs_{LWD}} \tag{12}$$

Where the compactness of LWD can be defined as a function of depth as $Vs_{1,sk}$, i.e. Vs corrected for gravel content (GC) and atmospheric pressure (pa= 1 atm ≈ 100 kPa ≈ 0.1 MPa), presented in Eq. (13)

$$\frac{Vs_{1,sk}}{Vs_1} \cong 1 - \frac{b \cdot GC}{1+e} \tag{13}$$

Vs1 is considered equal to Vs, normalized to 1 atm, as shown in Eq. (14), where b is a dimensionless parameter equal to 0.65 representing the contact ratio between GC gravel particles, the gravel content, expressed in decimals; and a term for the void ratio (1+e).

$$Vs_1 = C_v \cdot Vs = Vs \cdot \left(\frac{p_a}{\sigma_v'}\right)^{0.25} \tag{14}$$

The normalization coefficient C_v, must be equal to or less than 1.4 (Andrus and Stokoe 2000) and the vertical stress $\sigma' v$ corresponds to the mass of the residue at a given depth.

The results obtained indicate that the deposit has Vs1 ranges between 173 to 207 m/s, allowing to associate it to a stable state, and values below 180 m/s are associated with residual soils saturated at 85% or more, indicating instability. This approach allows obtaining a global approximation of the in-situ compaction state of LWD in different critical zones of the deposit. Also (Fourie et al. 2021), describes that it can be implemented when the project does not have a topography aim, since the estimated height depends on Vs and Tnak.

To determine geotechnical parameters, the use of Eq. (15) is proposed, determining the in-situ density as a function of depth and Vs, for ranges from 14 to 23 kn/m^3.

$$\gamma_t = 0.352 \cdot Vs^{0.283} \tag{15}$$

To validate these results, γ_t values are estimated from v_s and compared to a series of sand cone tests performed in another reservoir adjacent to the objective one. The values estimated by Eq. (15), underestimate the yt values at surface, but the increasing trend at depth (17.5 to 23.8 kn/m^3) is within the range of the material used. Fig.7, corresponds to the cohesion estimation based on the friction angle.

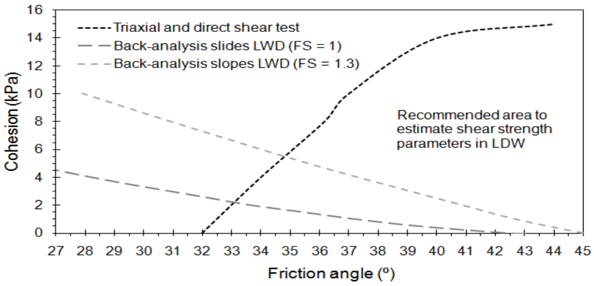


Figure 7. Abacus for estimation of shear strength parameters in leaching waste.

To estimate geotechnical parameters of the LWD, the P.A.N.D.A ® test was considered, obtaining and evaluating quickly a series of in-situ points with the friction angle through correlations and other indicators.

To evaluate the EF of the deposit, Eq. (15) was used, while the shear strength parameters were defined as a function of qd and estimation abacus Fig. 7. The calculation method is considered as: mongentern and price (1965), under static and seismic conditions (pseudostatic, kh=0.19), obtainingsafety factors (SF) in static, stable conditions and in pseudostatic unstable conditions (SF <1).

Regarding static liquefaction, considering the geometric configuration, slopes, characteristics of the deposited waste and site conditions identified by the values of Vs1, Tnak higher than 180 m/s, it is concluded that the static liquefaction potential is low, presenting an adequate stability in both seismic and static conditions.

1.7. Geostatistics applied to compaction control

The methodology proposed by (G. Villavicencio et al. 2022), proposes the use of geostatistical techniques to develop spatial models of in-situ density (yt) and degree of compaction for the periodic control of compaction in sand tailings dam embankments based on P.A.N.D.A ® cone resistance (qd), considering the variability of the material.

The material variability depends on the state of the structure and construction process. Being determined by the P.A.N.D.A® equipment, it finds the multilayer structure of the reservoir under construction and also obtains the geotechnical parameters to define low resistance sites. This kind of approach in geostatistics leads to periodic controlling through quality control (QC) or quality assurance (Qa) in compaction control processes. The variation of qd depends on the physical characteristics (particle size distribution and particle density), wop, standard Proctor (%SP) and layer thickness of the tailings and compaction method.

The geostatistical technique used corresponds to stochastic kriging (OK),comprising the information of the regionalized variable of qd and %sp through linear combination of the information, and where the phenomenon of the regionalized variable is weighted (variogram) and characterizes the geometry of the sample (value and location), subject to a universal quantification. The main advantage of this methodology is that it reduces the estimation error.

A 120 m wide and 45 m long study area of a newly constructed embankment is defined, where 91 PANDA tests are performed, being used to estimate QC up to 1.5 m, being separated every 7 m in sedimentation zones and 10 m of the embankment crest.

A geostatistical analysis is performed on historical data and data collected from the grid. Descriptive analysis, experimental variogram, theoretical variogram model and OK technique were performed.

The study allowed to define that qd evaluated at the global level of the study grid, follow a log-normal distribution, being smoothed using a 2.5 moving average to eliminate the noise of the signal recorded in-situ. In addition, the vertical direction experimental variogram study reflects that the multi-layer structure of the construction and compaction process approaches a value of 0.6 m representing the global variability of the layers. Regarding the horizontal analysis, two structures of approximately 8 m and 33-34 m are defined, where Eq. (16) defines a global spherical model for the study grid, where 3 spherical structures are defined with variability 0.21, 0.40 and 1.62, horizontal range of 8.4, 36 and 40 m and vertical range of 0.6 m, where the latter has no variability.

$$y(h) = 1.62sph(8.4, 8.4, 0.6) + 0.4sph(36,36,0.6) + 0.21sph(40,40, 0.6) \tag{16}$$

Considering Eq. (16), a spherical variogram model is used to estimate qd, where the results indicate that 95% of the estimated values are equal to or less than 4.5 Mpa. It considers a cross validation where the interpolated results and real values have a determination coefficient R2 (0.82 to 0.86) for each estimated penetrogram. Because of this, it proposes a correlation between qd and $\gamma_d$in Eq. (17).

$$\gamma_d = 1.11ln(q_d) + 17.25(kN/m^3) \tag{17}$$

Where the values range between 17 and 21.5 kN/m^3 and the compaction %SP varies between 90 and 100%, indicating that these ranges are similar to the statistical analysis from the routine layer-by-layer compaction control. Therefore, this correlation can be used for post-construction controls of tailings embankments, to identify areas with weak resistance or percentage below the project design values ($SP \geq 95\%$) and to optimize the compaction process.

1.8. Uncertainty

The level of uncertainty associated with the above correlations is high due to the variability of the mineralogical origin and method of construction of the tailings dams. The use of P.A.N.D.A® equipment allows to significantly reduce the uncertainty in both depth and spatial considerations, due to its speed in collecting and processing information. In addition, the use of geostatistical techniques, shown in point 1.8, establishes a strong regression to estimate the dry density of the material, establishing validation ranges in depth of the spatial correlation. Furthermore, the scope proposed in section 1.6 considers the combination of the information provided, but not the imperfection of the information: uncertainty, vagueness, incomplete and incoherent information, etc. For this reason, other tools could be implemented, such as the mass of beliefs, which considers the imperfection of the information and thus reduce the uncertainty and help in decision making.

2. Conclusions

This paper presents a series of studies using the P.A.N.D.A® test, which has shown great potential for improving decision making in pre and post-construction control of tailings dams. This test has been used for a variety of purposes: compaction control, determination of friction angle and relative tailings density, evaluation of liquefaction potential, tailings dam strength analysis, geostatistics and as an approach to monitoring other types of tailings impoundments.

By combining the versatility of the P.A.N.D.A® test with more specific approaches and more advanced techniques, such as geostatistics (krigring) and deterministic (IDW), it is possible to reduce uncertainty and ensure safe and effective monitoring of tailings dam and other type of deposit. This combination is particularly useful because it allows information to be gathered quickly, making it easier to identify the state of the layers in the case of compaction monitoring. These new studies make it possible to open a gap for more advanced studies to explain model uncertainty, data combination, estimation and decision making, concluding tin more reliable values.

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