INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

Evaluation of the physical stability of leaching waste deposits for the closure stage

Évaluation de la stabilité physique des dépôts de déchets de lixiviation pour la phase de fermeture des sites

Andy Fourie
Civil, Environmental and Mining Engineering, University of Western Australia, Australia, andy.fourie@uwa.edu.au

Gabriel Villavicencio, Juan Palma & Pamela Valenzuela
Grupo de Geotecnia, Escuela de Ingeniería en Construcción, Pontificia Universidad Católica de Valparaíso, Chile

Pierre Breul
Institut Pascal, Université Clermont Auvergne, Clermont Auvergne INP, France.

ABSTRACT: Leaching waste deposits are structures used for the storage of residues generated by hydrometallurgical processes for obtaining copper. Although the mechanical behavior of these types of deposits have historically remained adequate in seismically active countries like Chile, it is necessary to evaluate – for closure and post-closure stages – long-term physical stability, potential failure mechanisms, slope stability, and seismically induced deformations. However, the physical and chemical characteristics of such materials impedes geomechanical characterization via traditional *in-situ* and laboratory tests. Thus, this article presents a cost-efficient methodology to be implemented in evaluating long-term physical stability of leaching waste deposits. We identify the main contributing failure mechanisms, estimate *in-situ* conditions, and present the geomechanical parameters for stored material most suitable for analysis.

RÉSUMÉ : Les déchets de lixiviation générés par le procédé hydrométallurgique d'obtention du cuivre sont stockés en dépôts. Bien que dans des pays sismiquement actifs comme le Chili, les dépôts de ce type aient toujours eu un comportement mécanique approprié, il est nécessaire d'évaluer leur stabilité physique à long terme pour les phases de fermeture et de post fermeture. Pour ce faire, il est nécessaire de déterminer les mécanismes de défaillance potentiels, en évaluant à la fois la stabilité des talus et les déformations sismiques induites. Cependant, les caractéristiques physiques et chimiques de ce type de matériaux rendent très difficile leur caractérisation géomécanique par des essais classiques en laboratoire et sur site. Cet article présente une méthodologie économiquement abordable, développée pour être mise en œuvre dès les premières étapes du projet, qui permet d'évaluer la stabilité physique à long terme des dépôts de résidus de lixiviation, en identifiant les facteurs définissant les principaux mécanismes de défaillance, en estimant l'état *in-situ*, les paramètres géomécaniques présentés par le matériau stocké et en définissant les méthodes de calcul les plus appropriées.

KEYWORDS: leaching waste deposits, physical stability, closure stage, geomechanical characterization.

1 INTRODUCTION

As one of the world's leading copper exporters, Chile is expected to produce up to 6.32 Mton of copper concentrate and SX-EW cathodes by 2028 – a 13.9% increase compared to 2016. However, the latter cathode production may face a sustained decline over the next decade: from 2009-2016, the total production of SX-EW cathodes receded from 2,100 to 1,700 Kton, and is estimated to be even lower – 545 Kton – by 2028 (Cochilco, 2019) due to fewer economically viable deposits. For this reason, cost-efficient solutions are critical for current and future leaching sites to optimize overall copper oxide production processes, including those that ensure physical stability (PS) of the leaching waste deposits (LWD) during their useful life and in the long term in the closure stage.

Free from disasters that could have affected people, facilities, and/or the environment, the mechanical behavior of LWDs have largely proven adequate in seismically active Chile. However, Law 20,551 – which regulates Closure of Mining Sites and Facilities – requires mining companies to plan and implement a Closure Plan and respective PS measures for LWDs. In this regard, the National Geology and Mining Service (SERNAGEOMIN) has provided national mining companies with a "Methodological Guide for Evaluating the Physical Stability of Remaining Mining Facilities" (SERNAGEOMIN, 2018) to evaluate closure and post-closure stage LWD PS.

This methodology requires gathering copious background information related to the design project, construction methods, deposition rates, geotechnical controls, etc., executed during the operation stage. However, data series are usually unavailable, and even though geotechnical characterizations may be made from stored debris and *in-situ* and laboratory measurements, they tend to be oversimplified because of: i) limited economic resources; ii) lack of enough field surveys; and iii) inadequacy of *in-situ* and laboratory tests in properly determining physical and chemical characteristics of leaching waste. Given these limitations, PS analyses are performed considering: i) the "expert judgment" of the specialist geotechnical engineer; ii) supposing homogeneity of the internal structure of the deposit and leaching waste; and iii) estimation of geotechnical parameters for leaching waste from bibliographic data obtained in natural soils of similar physical characteristics. Clearly, the above degrees of uncertainty compound when attempting to characterize the physical stability of LWDs.

In addressing the above, then, this paper presents a methodology to evaluate LWD PS using low-cost data acquisition tools (Unmanned Aerial Vehicle (UVA) image, geotechnical and geophysical surveys) to generate a database on leaching deposits and provide correlated geotechnical parameters for them. Furthermore, this methodology allows for the necessary geotechnical information to evaluate the LWD PS to be generated at any stage, providing advance information on the main instability mechanisms and on critical areas or sectors.

2 INSTABILITY MECHANISMS AND EVALUATIONS OF PS IN LWD CLOSURE

2.1 *Physical instabilities*

Instability mechanisms in LWDs mainly stem from activating failure thresholds. These may take the form of slope failures, with surface failures or those induced by a basal plane interface between waste/geomembrane/foundation soil; and/or, to a lesser degree, static liquefaction.

2.1.1 *Slope failures*

National and international experiences suggest that the most common landslides in LWD are of the semicircular or basal "wedge" type, with tensile cracks in the crest or berm of terraces (Figure 1a). These result from the numerous potential failure surfaces, defined both by transitional slopes, generated during the operational stage of the reservoir; and by the existence of interfaces where the waterproofing and leachate collection systems are placed in these works, e.g., that of the "waste-geomembrane-foundation soil", at the basal level of the reservoir, and the "waste-geomembrane-waste" between terraces. The potential failure planes generated during the operation of the deposit are those of low shear strength, with less interlocking between particles in relation to the entire mass of waste, caused by post-peak or residual shear strength (Smith & Giroud, 2000). This occurs where material is deposited by overturning and adopts a slope defined by the friction angle of the shifted material and its large deformations, resulting in granulometric segregation. In turn, surface failure creates mechanically unstable zones which are currently – or will be – interconnected with planes at the basal interface in the foundation seal and/or in each terrace.

Next, any change in the saturation state of deposited waste heap – e.g., as is the case during secondary leachings, infiltrations, and/or internal water flows – may activate acid solutions present, which can penetrate into the micro-cracks of particles to produce an effect called "chemical crushing" and a greater percentage of fine particles (Bard & Campaña, 2004). This effect decreases permeability and strength parameters of the leaching waste, increasing the probability of failure in the LWD slopes.

2.1.2 *Static liquefaction*

Another failure mechanism, although less common, in LWDs is that of static liquefaction. This phenomenon, which occurs mainly on heap slopes, is characterized by the sudden loss of shear strength in loosely deposited waste moving from a drained to an undrained condition. This generates a rapid increase in pore pressures due to the weight of the deposited material itself (and more so, under secondary leaching). Here material flow or deformations of varying magnitude may be generated (Figure 1b).

This phenomenon is most common in recently deposited leaching waste, subjected to secondary leaching, and/or affected by groundwater flow through the deposit, and which have percentage of fines (F.C) below 20%, *in-situ* conditions classified as loose (low density material deposition, overturned from transport trucks), a degree of saturation (S) equal to or greater than 85%, and under increasing loads (Thiel & Smith, 2004; Bard & Campaña, 2004).

As time stretches toward the end of the operation stage, this type of material hardens, or "matures", in strength parameters due to factors such as: i) natural loss of moisture from ambient temperature; ii) densification from construction processes and the weight of the materials themselves (overburden height); and iii) progressive intergranular cementation, cohesion among the clayey fine fraction of the waste, residual minerals, and chemical substances from the leaching process.


a) b)

Figure 1: Physical instabilities in LWD. a) Slope failure with tensile cracks at crest; b) Failure due to static liquefaction.

2.3 *Methodology for the evaluation of PS*

The official methodology for evaluating PS in a LWD is structured into four main stages (SERNAGEOMIN, 2018), summarized below.

(a) Stage No. 1, potential impact to the environment. Classifies potential environmental impact in case of a failure due to physical instability in the closure and post-closure stage of an LWD, considering the following factors: height and volumetric capacity; number of people to evacuate; and level of impact to environments downstream the mining deposit. Each factor is assigned a score. From the sum of the scores, the potential environmental impact of the LWD is determined (low, significant, high, and extreme).

b) Stage No. 2, potential for failure. Each instability mechanism is gauged for potential failure, considering the following groups of factors: i) foundation conditions, i.e., geotechnical characteristics of the foundation soil, slope of the foundation, and foundation soil/deposit interface, topographic shape; ii) geometric configuration of the deposit, i.e., overall height, slope angle, maximum bench height, maximum vertical thickness; iii) construction background, i.e., loading or deposition rate of leach waste (volumetric loading, loaded weight, length of crest); filling sequence and bench height; iv) physical characteristics of deposited materials (granulometry and plasticity of fine fraction), *in-situ* compactness, permeability; undrained and drained shear strength; v) history of instrumentation and monitoring, recorded and analyzed; vi) regional environment defined for the closure condition; vii) physical stability observed during the operational stage; and viii) degree of implementation of measures to ensure physical stability in the closure stage. Each of the factors considered in each group is weighted according to the condition of the LWD. Instability mechanisms (slope instability, displacements and heaps greater than those considered in the design project for the Closure and Post Closure stage, and static liquefaction) are graded on groups of factors. Once an evaluation has assigned scores to each factor, they are added together to provide the objective potential for failure occurrence (low, significant or high).

c) Stage 3: Category of methods used to evaluate PS. Based on potential environmental impact and occurrence of failure, each mechanism may have its PS evaluated by methods that are: simplified, intermediate and complex.

d) Stage No. 4, calculation methods for PS analysis during evaluation of closure and final closure. Each mechanism is analyzed by the most appropriate evaluation method. For slope stability: i) simplified, static/pseudo-static limit equilibrium methods; ii) intermediate, static/pseudo-static limit equilibrium methods and deformation analysis by simplified methods; and iii) complex, static/pseudo-static limit equilibrium methods, deformation analysis by simplified methods, and numerical methods. For static liquefaction: i) simplified, semi-empirical methods based on correlations with *in-situ* tests; ii) intermediate, methods based on correlations with *in-situ* and laboratory tests; and iii) complex, methods based on correlations with *in-situ* and laboratory tests and numerical methods.

3 MATERIALS AND METHODS

Our proposed methodology seeks to improve upon the above, and so, to evaluate PS in LWD at the closure stage, four fundamental steps were defined: i) baseline for deposit, site, and sector; ii) field work and identification of critical zones in the LWD; iii) estimation of *in-situ* conditions and geotechnical parameters of leach waste at LWD critical zones; and iv) evaluation of PS at the closure stage.

3.1 *LWD Baseline Establishment*

To generate a baseline for the LWD, the proposed method takes as input the project design, construction background, operation and geotechnical information of the stored leachate waste, basal interfaces, and foundation soil. This work considers one experimental LWD (LWD 1) located in northern Chile, projected to store 12 million m^3, geometrically stepped with benches and berms to a maximum height of 65 m. In general terms, the construction methodology started with basal waterproofing of the foundation soil (double-textured geomembrane), leaching waste transported from the plant, and deposited by dump truck. Once at the LWD, waste dries at ambient temperature until it reaches below 15% site humidity, when it is distributed by bulldozer to form benches and terraces. Material is compacted by construction machinery during the process itself. Next, while leaching waste is a geotechnically complex material of broad physical and chemical characteristics, it is generally understood as gravels, sands and low plasticity clays (GC-SC, SC or GC). A summary of the geotechnical properties of the leaching waste deposited in the experimental LWD is presented in Table 1.

Table 1. Geotechnical properties of leaching waste. Values and statistical analyses of experimental data from two representative LWD.

Geotechnical Properties	Average	Coefficient of variation (%)
Specific gravity, G	2.8	3.7
Median grain size D_{50} (mm)	3.7	29.5
Percentage of fines less than 80 (μm), F.C (%)	14	23.5
Plasticity index, IP (%)	15	38
Proctor maximum dry unit weight, γ_{dmax} (kN/m^3)	2.09	8.1
Optimal water content, w_{op} (%)	9.5	5.4
Dry unit weight *in-situ*, γ_d (kN/m^3)	1.92	10.4
Water content *in-situ*, w_{nat} (%)	8.5	26.9
Effective friction angle, ϕ‘ (°)	41	6.4
Effective cohesion c’(kPa)	10	60.5

3.2 *Identification of critical zones in LWDs*

Critical zones in LWDs are identified in two stages: (i) Visual inspection of the deposit and information gathering by an expert; (ii) Generation of a digital elevation model (DEM) from images captured by an unmanned aerial vehicle (UAV) in order to obtain deposit geometry (total height of the deposit, overall slope angle, height and angle of banks, width of berms) (see Figure 2) and zones showing signs of local material landslides (See Figure 3).

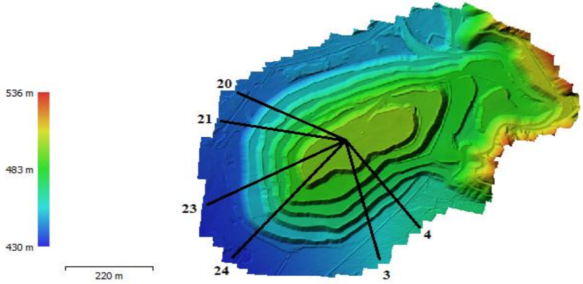

Figure 2. Geometrically critical zones and profiles, with analysis sites (3, 4, 20, 21, 23 and 24). DEM model. Experimental LWD 2.

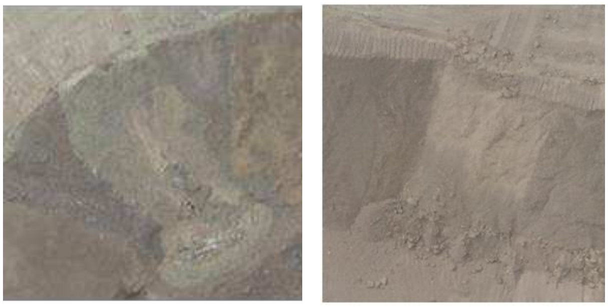

Figure 3. Images of local landslides on LWD 2 terrace slopes.

3.3 *Prospecting and geotechnical parameterization of LWD critical zones*

We prospected the LWD for critical zones and estimated the *in-situ* condition of waste stored at depth by a reconnaissance campaign utilizing geotechnical and geophysical surveys (see Table 2).

The results were referenced against a database of geotechnical parameters for waste, bibliographic correlations and estimation criteria, and yielded deposit height and *in-situ* conditions for hardness and shear strength (angle of friction and cohesion) of the heaped waste.

Table 2. Geotechnical and geophysical surveys for LWD.

Type of prospection	*Result*
Dynamic penetrometer PANDA	Tip resistance (q_d) in depth
MASW and MAM	Shear wave velocity (Vs) in depth
Spectral ratio H/V	H/V Spectral ratio v/s frequency

3.3.1 *LWD in-situ conditions, leach tailings and height*

Due to costs associated with prospecting heap depth, *in-situ* surveys like geotechnical drilling or CPTu tests are limited or non-existent. To remedy this, this proposal uses alternative surface geophysical prospecting tests like MASW (Multi-Channel Analysis of Surface Waves) and MAM (Microtremor Array Measurements) with the Nakamura technique.

Briefly, the seismic response of a soil deposit depends mainly on its low deformation hardness in upper strata, and its fundamental period (Verdugo, 2019). To seismically classify a soil reservoir, the shear wave velocity (Vs) - complemented with stratigraphy and other geotechnical parameters (e.g: q_u, RQD,

N_1, Su, etc.) – constitutes a common first order parameter considered in several normative codes of structural design (e.g., DS-61, IBC, ASCE7-10, Code for seismic design of building China, among others). These codes globally advocate different soil types and stratigraphic profiles, including a descriptor of the *in-situ* state for different ranges of Vs. In Chile, the predominant period of the site has also recently been accepted as a complementary parameter for the so-called Nakamura Method (Nakamura 1989), which takes environmental vibrations and the HVSR spectral ratio to obtain the Nakamura period (T_{nak}). With *a priori* knowledge of the materials and internal structure of an LWD, it is reasonable to use the following ranges of Vs and T_{nak} (HVSR) in estimating the *in-situ* waste condition, as well the hardness of the reservoir foundation soil: i) Vs ≤ 180m/s (medium consistency soils); ii) 180m/s ≥ Vs > 350m/s and T_{nak} < 0. 75s (medium-dense or medium firm soils); iii) 350m/s ≥ Vs > 500m/s and T_{nak} < 0.4s or flat HVSR (dense or firm soils); 500 ≥ Vs > 900m/s and T_{nak} < 0.3s or flat HVSR (soft or fractured soils, very dense soils); Vs > 900m/s and T_{nak} < 0.15s or flat HVSR (rock or cemented soil). It is possible to simply approximate LWD height (H), according to the values of Vs obtained for the reservoir (Vs_{LWD}) and the T_{nak} period (T), by iteration (Eq. 1), under the following conditions: horizontal stratified structure, elastic-linear mechanical behavior characterized by Vs (Vs_{LWD}), and foundation soil of higher hardness.

$$T = \frac{4\cdot H}{Vs_{LWD}} \tag{1}$$

Next, the compactness of leach waste may be defined as a function of depth using parameter $Vs_{1,sk}$ (Chang et al., 2016), i.e., Vs corrected for gravel content (GC) and atmospheric pressure (pa= 1 atm ≈ 100 kPa ≈ 0.1 MPa), presented in Equation 2.

$$\frac{Vs_{1,sk}}{Vs_1} \cong 1 - \frac{b\cdot GC}{1+e} \tag{2}$$

where Vs_1 is Vs, normalized to 1 atm (see equation 3); b, a dimensionless parameter equal to 0.65 representing the proportion of gravel interparticle contact (Thevanayagam and Liang, 2001); GC, gravel content, expressed in decimals; and a term for the void ratio (see equation 3).

$$Vs_1 = C_v \cdot Vs = Vs \cdot \left(\frac{p_a}{\sigma'_v}\right)^{0.25} \tag{3}$$

where C_v is the normalization coefficient, equal to or less than 1.4 (Andrus et al., 2000); and σ'_v is the effective vertical stress of the waste mass at a given depth.

The limit for stable $Vs_{1,sk}$ is 220 m/s, indicative of a dense to medium dense state and granulometric characteristics as discussed in previous studies on seismic liquefaction of sand and gravel soil deposits (e.g., Kokusho, 1995; Cao et al., 2011; Hubler et al., 2018, among others). Otherwise, values below 180 m/s are associated with leaching waste saturated at or above 85% - an indicator of physical instability. An example of application is presented in Table 3.

In our case, the values of parameter $Vs_{1,sk}$, range from 173 to 207m/s, associated with a medium dense state of compactness.

The results allow us to obtain a first global estimate of the *in-situ* compactness state of the leaching waste in critical zones of the deposit. Next, although the estimated height (H) values slightly differ from the topographic height of the LWD, the proposed method constitutes an interesting alternative to be used in cases where no previous topographic information on the foundation soil of a LWD is available.

Table 3. Estimation of height and site conditions at LWD 1.

Depth m	Vs m/s	Vs_{LWD} m/s	T_{nak} s	Height (m) Real	Height (m) Estimated	Conditions *in-situ*
0 – 7.9	280	317	0.52	40	47	Medium -dense waste
7.9 – 15.7	297					
15.7 - 23.6	313					
23.6 - 31.5	329					
31.2 – 39.3	345					
39.3 - 47.2	361					
47.2 - 55.1	377	-		-	-	Foundation soil: quaternary alluvial deposits
55.1 – 62.3	394	-				
62.3 – 70.8	410	-				

3.3.2 *Estimation of geotechnical parameters*

a) The *in-situ* density is estimated following Anbazhagan et al. (2016), i.e., as a function of depth and of Vs, for a range of 14 to 23kN/m^3 (Equation 4).

$$\gamma_t = 0.352 \cdot Vs^{0.283} \tag{4}$$

To validate this correlation, γ_t values were estimated from the LWD 1 Vs and compared with a series of sand-cone tests performed on some benches of each reservoir. Although Equation 4 is known to underestimate surface γ_t values, the increasing trend as a function of depth (17.5 to 23.8 kN/m^3) is within the range of values expected for this type of material. The C_v for each bench was less than 25%, allowing for the supposition of a homogeneous γ_t and of the estimated *in-situ* condition as medium dense.

b) Shear strength parameters were estimated using background information collected and generated in LWD 1: i) database of triaxial and direct shear tests; ii) friction angle and cohesion estimation abacuses were generated from back-analysis of local landslides and intact slopes in benches (Wesley et al., 2001), with slopes from 31 to 33° (LWD 1). Figure 4 shows an example of the estimation abacus obtained for LWD 1.

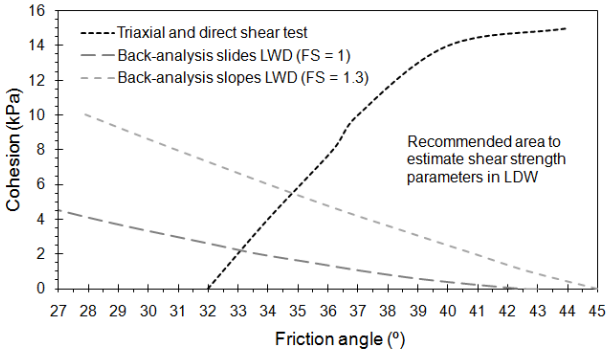

Figure 4. Abacus for estimation of shear strength parameters in leaching waste.

Leaching waste in early stages of deposition in the field are likely to present predominantly frictional mechanical behavior. In this sense, the PANDA dynamic penetrometer is attractive to quickly obtain and evaluate a series of *in-situ* survey points, up to a maximum depth of 6m (e.g., Gourvès and Barjot, 1995; Villavicencio et al., 2011). The penetrometer signal (see Figure 5a) is taken with the ratio q_d/q_c = 1.03 (e.g.: Chaigneau, 2001, Rahim et al., 2004) and the normalized tip resistance (q_{dN1}), for which the ratio proposed by Jefferies and Been (2006) adequately estimates parameter ϕ' (see Figure 5b).

3.4 *Evaluation of PS for the closure stage*

Based on the background information collected and generated as part of this work – and using the classifications of the official PS evaluation methodology of a closure stage LWD (SERNAGEOMIN, 2018) – results were as follows:
a) Potential impact to the environment, low. b) Potential for occurrence of failure, i) Slope instability: significant; ii) Static liquefaction: low. c) Category of methods to be used for PS evaluation in i) Slope instability: intermediate; ii) Static liquefaction: simplified. d) Calculation methods to be used for i) slope instability: static/pseudo-static limit equilibrium methods and deformation analysis by simplified methods; ii) Static liquefaction: semi-empirical methods based on correlations with *in-situ* tests.

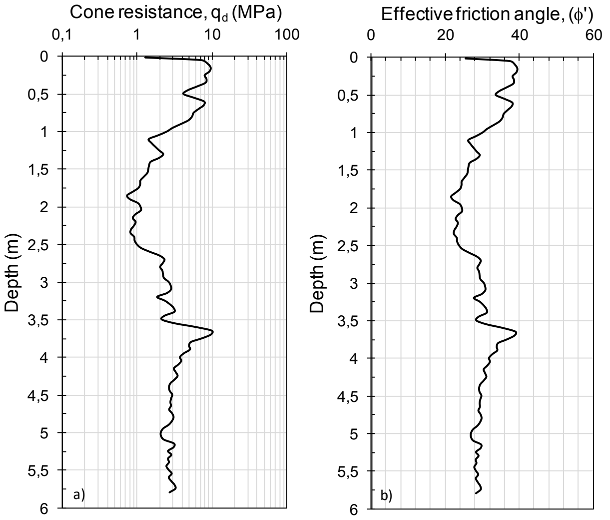

Figure 5. Test Nº 1. LWD 1. a) Tip resistance q_d as a function of depth. b) Estimation of ϕ' as a function of depth.

3.4.1 *Slope Stability*

The analyses of slope stability in the critical zones of LWD 1 considered the *in-situ* condition of heaped waste, obtained from the proposed method as a function of Vs. The shear strength parameters were defined based on q_d and the estimation abacus. Calculations followed Morgentern and Price (1965), under static and seismic conditions (pseudo-static, with $K_h = 0.19$). The factor of safety (FS) acceptability criteria for PS were defined in terms of consequence and reliability, as proposed by Hawley & Cunning (2017). The geometric profiles of the critical zones indicate that FS values, under static conditions, vary between 1.29 and 1.50; and, under seismic conditions, between 0.93 and 1.42. Given the low consequences (defined from the potential impact to the environment) and high reliability (in terms of the degree of accuracy of input parameters), the FS values indicate that LWD 1 presents an adequate physical stability under static conditions. In seismic conditions, however, potentially unstable sectors (FS < 1) were identified. For these areas, a simplified analysis of seismically induced displacements should be performed. For a record obtained in the region where LWD 1 is located ($a_{max} = 0.65g$), seismically induced displacements under the sliding block method initially proposed by Newmark (1965) should be less than 10cm.

3.4.2 *Static liquefaction*

Considering the geometric configuration of LWD 1, the slope of the foundation soil, characteristics of deposited waste and the *in-situ* condition defined by $Vs_{1,sk}$ values over 180 (m/s), it is concluded that the static liquefaction potential of this deposit is low, i.e., LWD 1 generally presents adequate physical stability. This is fully consistent with the mechanical behavior observed during its operational stage. In fact, according to the information gathered for this experimental deposit, under both static and seismic conditions, no physical instabilities globally compromised its structure or nearby environment during its operational stage

As an example, during the seismic event in the central-northern regions of Chile on September 16, 2015 (Mw = 8.3, epicenter in the subduction zone near *Illapel*), this deposit maintained overall adequate mechanical behavior. In the long term, PS seems to have increased due to the hardening or "maturation" effect due to progressive drying.

4 CONCLUSIONS

This paper presented a methodology to evaluate PS in LWDs for their closure and post-closure stages using low-cost data acquisition tools (UVA imaging, geotechnical and geophysical surveys) during operational stages of the facility, and geotechnical criteria to estimate both the *in-situ* condition and shear strength parameters in leachate waste. The application of this methodology allows researchers to:

- Geotechnically characterize leach waste as a function of depth, prospecting larger surface areas. This is an important advance, particularly for average LWD across the copper mining sector, since these deposits usually maintain superficial geotechnical controls (e.g., sand cone and sample extraction) and, to some degree, deep prospecting (e.g., DCPT penetrometers).
- Identify and analyze the critical zones or sectors in LWDs, in terms of geometry and *in-situ* condition, especially when evaluating the main instability mechanisms that could be generated in this type of reservoir at any stage of its useful life or where complementary surveys may later be carried out (e.g., geotechnical drilling, CPTu, among others).
- Estimate the height of LWDs from cross-comparison of surface geophysical surveys (MASW, MAM and Nakamura), especially where PS analysis may not otherwise be available.
- Estimate shear strength parameters, by means of *in-situ* surveys (PANDA penetrometer) and estimation abacuses, as an alternative to triaxial or direct shear tests, which are difficult to perform in the laboratory, due to the physical and chemical characteristics.
- To evaluate the feasibility of applying secondary lixiviation in LWDs from the point of view of the PS of the deposit, an aspect of relevance for the mining business.

5 ACKNOWLEDGEMENTS

Our sincere thanks and forever appreciation to Professor Claude Bacconnet†, for his relevant contributions in the discipline of geotechnics, in particular to the mechanics of granular media and spatial variability of geotechnical parameters.

6 REFERENCES

Anbazhagan P. Uday A., Moustafa S. and Al-Arifi N. 2016. Correlation of densities with shear wave velocities and SPT N values. *Journal of Geophysics and Engineering* 13 (3), 320–341

Bard E. and Campaña J. 2004. Aspectos geotécnicos en el diseño de pilas y botaderos de lixiviación. *V Congreso Chileno de Ingeniería Geotécnica, Santiago, Chile.*

Cao Z., Youd L., and Yuan, X. 2011. Gravelly soils that liquefied during 2008 Wenchuan, China earthquake, Ms=8.0. *Soil Dynamics and Earthquake Engineering*. 31(8), 1132–1143

Chang, W.J. 2016. Evaluation of Liquefaction Resistance for Gravelly Sands Using Gravel Content–Corrected Shear-Wave Velocity. *Journal of Geotechnical and Geoenvironmental Engineering.* 142 (5), 04016002.

Cochilco 2019. *Proyección de la producción de cobre en Chile 2018 – 2029,* Comisión Chilena del Cobre, Santiago, Chile.

Gourvès R, and Barjot R. 1995. The Panda ultralight dynamic penetrometer." *In Vol. 3 of Proc., 11th Euro. Conf. on Soil Mechanics Foundation Engineering,* Danish Geotechnical Society, Copenhagen, Denmark, 83-88.

Hawley M. and Cunning J. 2017. Guidelines for Mine Waste Dump and Stockpile Design. CRC Press.

Hubler J., & Zekkos A. and Zekkos, D. 2018. Monotonic and cyclic simple shear response of gravel-sand mixtures. *Soil Dynamics and Earthquake Engineering*, 115, 291–304.

Jefferies, M.G. and Been, K. 2006. *Soil liquefaction – A critical state approach.* Taylor & Francis Group, London and New York.

Kokusho T., Tanaka Y., Kawai T. Kudo K., Suzuki K., Tohda S. and Abe S. 1995. Case Study of Rock Debris Avalanche Gravel Liquefied During 1993 Hokkaido-Nansei-Oki Earthquake. *Soils and Foundation* 35 (3), 83-95.

Morgenstern N.R. and Price V.E. 1965. The Analysis of the Stability of General Slip Surfaces. *Géotechnique* 15 (1), 79-93.

Nakamura Y. 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Report of RTRI* 30 (1), 25-33.

Newmark M.N. (1965). Effects of earthquakes on dams and embankments. *Geotechnique* 15 (2), 139–160.

Rahim, A., Prasad, S. and George, K. 2004. Dynamic cone penetration resistance of soils-theory and evaluation. *Int. Conf. Geo-Trans 2004*, L.A, California, 1755–1766.

SERNAGEOMIN 2018. Guía Metodológica para Evaluación de la Estabilidad Física de Instalaciones Mineras Remanentes. Ministerio de Minería de Chile.

Smith, M.E. and Giroud, J.P. 2000. Influence of the direction of ore placement on the stability of ore heaps on geomembrane-lined pads. *Slope stability in surface mining, Chapter 49, Society of Mining Engineers,* W.A. Hustrulid, M.K. McCarter and D.J.A. van Zyl (eds).

Thevanayagam S. and Liang J. 2001. Shear wave velocity relations for silty and gravely soils. *In Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,* San Diego, California, 1. 1-7.

Thiel R.S. and Smith, M.E. 2003. State of the practice review of heap leach pad design. *Geotextiles and Geomembranes* 22 (6), 555-568.

Verdugo R. 2019. Seismic site classification. *Soil Dynamics and Earthquake Engineering* 124, 317-329.

Villavicencio, G., Breul P. Bacconnet C., Boissier D. and Espinace R. 2011. Estimation of the variability of tailings dams properties in order to perform probabilistic assessment. Geotechnical and Geological Engineering 29 (6), pp 1073-1084.

Wesley L.D and Leelaratnam V. 2001. Shear strength parameters from back-analysis of single slips. *Géotechnique* 51 (4), 373-374.