The Effects of Confining Pressure, Density and Tailings Water Content on the Cone Resistance of Dynamic Lightweight Penetrometers

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ABSTRACT

Dynamic Lightweight Penetrometers (DLP) are an attractive technology when prospecting tailings storage facilities due to their low cost, ease of transportation and use. One of the shortcomings of LPs is that their sounding depth is usually limited to less than 10 m. Thus, DLPs are not intended to fully replace conventional penetrometers when deep characterization of soils is required. However, are an attractive tool for routinary control of dams. Lightweight penetrometers have been used in Chile in recent decades as a tool for monitoring the compaction degree of retaining walls in tailings dams. In addition to this, DLPs have been used in thickened tailings deposits to characterize stiffness and strength of materials. For instance, a series of correlations between DLP's cone resistance (q_d) and friction angle (ϕ) and undrained shear strength (S_u) of thickened tailings have been proposed. There have also been a series of efforts to correlate q_d with the tip resistance of other well documented techniques, e.g. CPT, SPT, DSPT. Nevertheless, there still exist a series of uncertainties related to the effects of tailings state parameters, e.g. water content (w %), confining pressure (σ'_v) and void ratio (e), on the resulting q_d. This is experimentally explored in the present study using a pressure chamber under controlled conditions. The outcomes of this study will contribute for the rational interpretation of DLP's results when used for the monitoring of tailings dams.

INTRODUCTION

As a result of the production of copper and other minerals, Chile produces over 1.6 million tons of mine tailings per day. The strategies adopted in last decades for the management of this material have resulted in the existence of more than 600 above-ground deposits (SERNAGEOMIN 2015). Most of these structures correspond to tailings dams constructed using cyclones, which generate coarse sands from full stream tailings.

Tailings dams are susceptible to failure when certain mechanisms, such as overtopping, piping, or liquefaction, are triggered in the embankment (i.e. main retaining sand walls). Although the design of these dams has significantly improved in the last 30 years along with the development of geotechnical, seismic and hydraulic disciplines (Villavicencio et al. 2014), failures still occur.

From a geotechnical point of view, the risk of failure in tailing dams can be significantly decreased if size distribution and compaction degree of tailings sands are adequately defined and strictly controlled during dam construction. For instance, it is commonly suggested that fines content in sands should be limited to 20% while a compaction degree greater than 95% of OPM (optimum proctor modified) dry density should be the target during construction. These recommendations are consistent with the scientific knowledge on seepage and shear response of sands, e.g. high degrees of compaction guarantee a dilatant and likely stiffening response of sands under monotonic or cyclic loading (Suazo et al. 2016b).

The control of surface compaction of sand tailings is usually performed using the sand-cone density apparatus or a nuclear densometer. These are inexpensive and reliable equipment. However, they do not allow to characterize the thickness of compacted layers or to verify density of the dam in depth. In this context, dynamic lightweight penetrometers (DLP), in comparison to conventional penetrometers (e.g. SPT, CPT, DCP-Standard), arise as an attractive technology for the routinary control of compaction (or density in depth). LDPs present a low cost, ease of transportation, storage and use (e.g. only one operator is needed). Previous research on the use of lightweight penetrometers have found that there exist a strong correlation between the dry unit weight of soil (γ_d) and DLP's cone resistance (q_d), following the expression:

$$\gamma_d = \alpha \cdot \ln(q_d) + \beta \tag{1}$$

Where α and β are best fitting parameters. The experimental studies of Villavicencio et al. (2012) have proved that this type of relationships are valid for tailings sands with R-squared of above 0.98. The authors also observed that water content might have a significant effect on q_d at a given density. The eq. (1), however, does not consider the effects of confining pressure (σ'_v), and therefore it must be corrected when surveying changes of density (compaction degree) with depth in dams.

In this context, the present study explores the effects of soil's state parameters, i.e. confining pressure, water content and density on the cone resistance of dynamic lightweight penetrometers.

The expressions presented in this article are aimed to provide tailings engineers with correction expressions that allow to verify density in tailings dams using a low cost and versatile technology.

METHODOLOGY

Materials

To understand the effects of the state parameters on q_d, a clean sand was used in this study. The material classify according to the Unified Soil Classification System (USCS) as well-graded sand (SW). The material shows a plasticity index of 0, a specific gravity of 2.65 and maximum and minimum total unit weight of 16 and 14 [kN/m^3], respectively. The particle size distribution is shown in Figure 1.

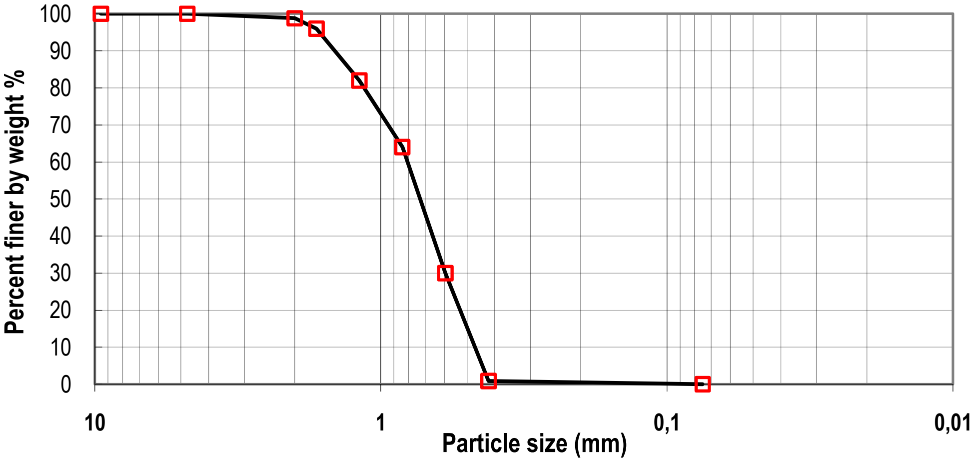

Figure 1 Material particle size distribution

Testing apparatus

A calibration chamber was constructed in order to control sand's state parameters (density, water content and confining stress) during penetration of the dynamic lightweight penetrometer. The chamber is 100 cm in height with an inner diameter of 40 cm. This diameter is 40 times larger than DLP's rod diameter. Vertical confining pressure is applied through a hydraulic jack which stresses a steel lid by means of a steel rod. To avoid friction in the rod and side walls a thin lubricated 1 mm polyamide was used. The location of the holes in the lid, through where the tests were conducted, are shown in Figure 2. The system is able to apply vertical confining pressures up to 1000 kPa. However, DLPs are usually used to explore the first 5 m below ground surface, and thus, a pressure ranging from 0 to 200 kPa was considered in the tests.

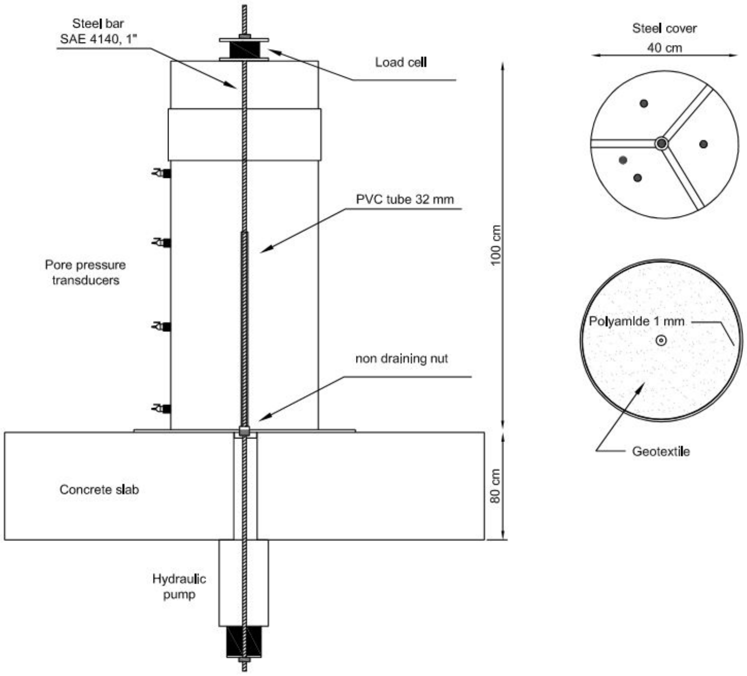

Figure 2 Schematic of the penetrometer chamber

The lightweight penetrometer used correspond to model PANDA developed in the early 90s by Dr Roland Gourves, which is now widely used in France (it complies with NFP 94-105) and other countries (Langton 1999). The test is carried out by driving a cone of 4 (cm^2) on the end of a rod using a fixed weight hammer of 2 kg. For each blow, a microprocessor records the speed, depth of penetration and amount of energy of the impact.

Testing plan

Penetration tests were conducted in samples prepared at different relative densities (i.e. 40, 60, 80 and 90%) and water contents (i.e. 1, 2 and 4%). The material was compacted in the chamber in 10 layers of 10 cm until the required relative density (RD%) was obtained. Confining pressure was increased in increments of 50 kPa. During the tests, confining pressure and changes in density are continuously recorded by means of a load cell and LVDT located on top of the lid.

RESULTS AND DISCUSSION

In order to explore repeatability of the test and the potential effects of chamber's boundary conditions on cone resistance, three tests were conducted at the same DR% and w% (Figure 3). In the figure it is observed that similar values of q_d are obtained in depth. In addition, signal stabilizes at a given depth in the so-called "critical depth" (Villavicencio et al. 2012).

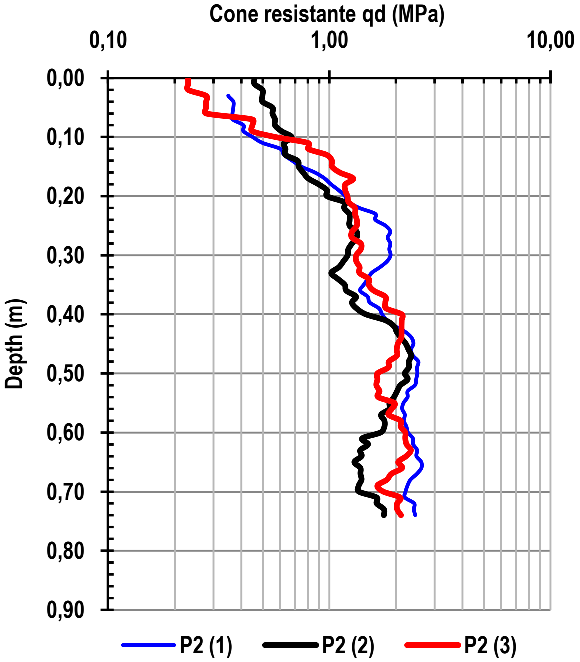

Figure 3 Lightweight penetrometer tests on sand. DR=70%, w=0%. Three repetitions

The effects of DR on q_d are summarized in Figure 4a. The results were obtained at $\sigma'_v = 0$ (surface of dams). It is shown that, as expected, cone resistance significantly increases when DR increases. In this figure, eq. (1) was best fitted to the experimental data rendering $\alpha = 0.91$ and $\beta = 14.3$ with R^2=0.97. This confirms that lightweight penetrometers are suitable to control compaction degree during construction and rising of tailings dams.

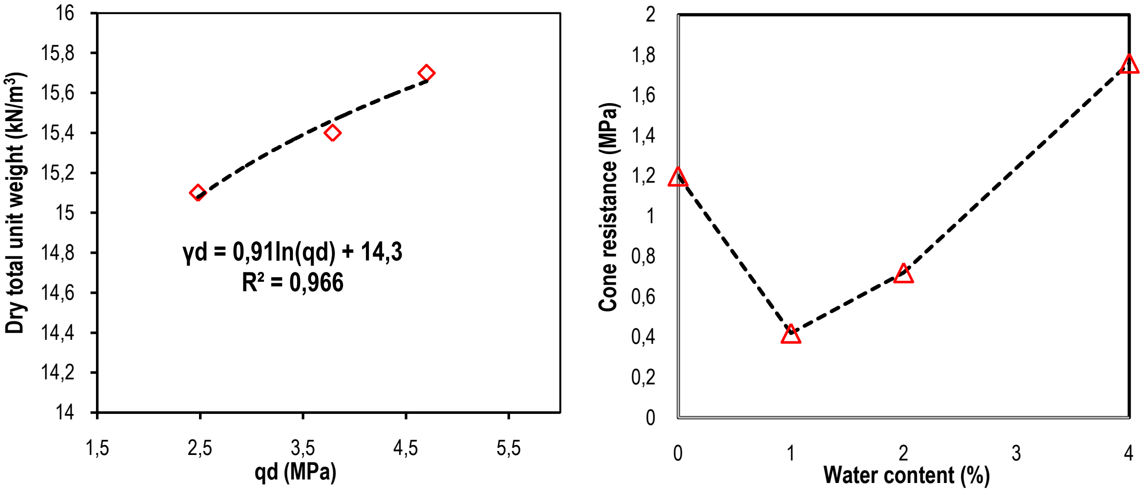

Figure 4 a) Dry total unit weight versus cone resistance and b) effects of water content on cone resistance

On the other hand, Figura 4b shows that q_d is affected by water content. As water content moves toward saturation, q_d increases. At low values of water content (w) the observed phenomenon can be attributed to pore suction. However, as water increases the DLP impact (compressional stress wave) is mostly transferred to water phase which shows a significant lower compressibility than soil skeleton (Suazo et al. 2016a), which may explain larger values of q_d. Therefore, the applicability of DLPs in nearly saturated soils needs further study.

In Figure 5, the evolution of q_d with respect to confining pressure (σ'_v) is presented. As expected, the higher the confining pressure (deeper in the dam) the higher q_d. Another important observation is that increased σ'_v causes a relatively constant value of q_d along the chamber, i.e. critical depth is not observed. This also confirms that the confining mechanism of the testing apparatus is applying pressure uniformly within the soil. In regard of the results presented in this figure, it is possible to propose a correction factor due to confining pressure (c_n).

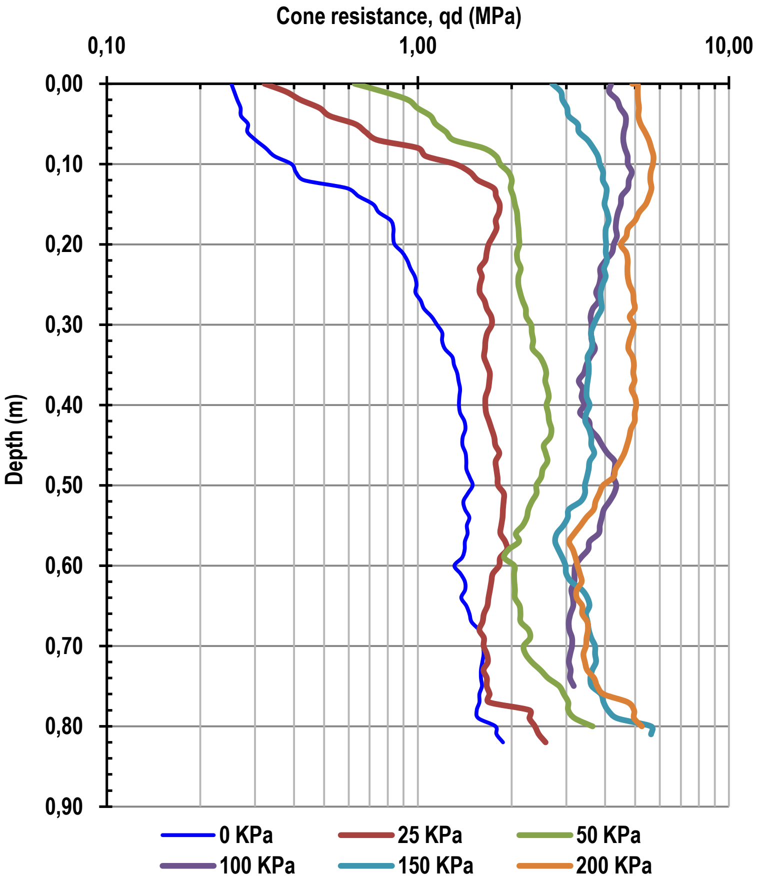

Figure 5 Effects of confining pressure on cone resistance. DR=60%, w=0%

Several expressions for c_n have been proposed in the past in the context of standard penetration tests (SPT). However, the expression of Boulanger (2003) is commonly used in practice (reevaluated from Marcuson and Bieganousky):

$$c_n = \left(\frac{P_a}{\sigma'_v} \right)^m \tag{2}$$

where P_a is the atmospheric pressure and m a fitting parameter. This equation was best fitted to the experimental data presented in this article (Figure 6). It can be observed that best fit value m is approximately 0.50 for all the tests considered. This is consistent with the values used in practice for SPT tests conducted in sand with low fines content.

Regarding the results of this study, a m value of 0.5 can be used when correcting DLP's cone resistance tests on dams with relatively low fines contents. The effects of increased fines contents is uncertain and thus needs to be further explored.

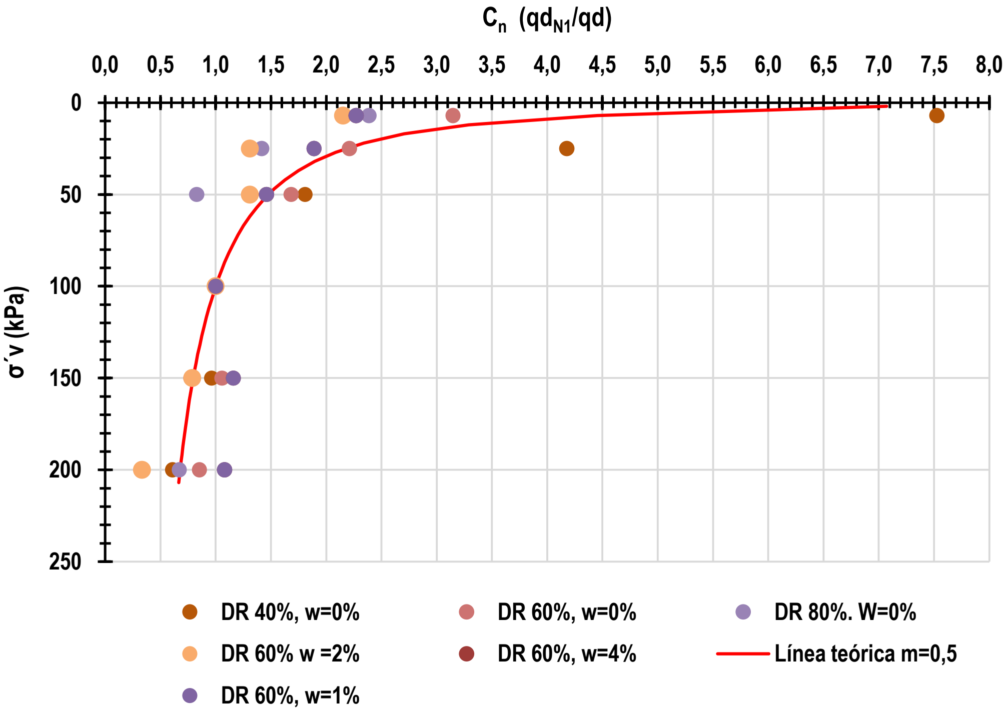

Figure 6 Overburden correction factor for lightweight penetrometers in sand

CONCLUSION

In this article, the effects of soil's state parameter (density, confining pressure and water content) on cone resistance of dynamic lightweight penetrometer were explored. As previously reported, there is a strong correlation between density and cone resistance in sand tailings. Thus, DLPs are an attractive alternative when controlling relative density during construction of tailings dams. In addition, it is observed that water content influences cone resistance. These effects can be significant when material is near saturation. Finally, an overburden stress normalization is proposed for DLPs in sandy material. This normalization can be used when surveying tailings dams.

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REFERENCES

Boulanger, R. W. (2003). “High Overburden Stress Effects in Liquefaction Analyses.” *Journal of Geotechnical and Geoenvironmental Engineering*, 129(12).

Langton, D. (1999). “The panda light-weight penetrometer for soil investigation and monitoring material compaction.” *Ground Engineering*, 32(9), 33–37.

SERNAGEOMIN. (2015). “Catastro de Depositos de Relaves.” Santiago, Chile, <www.sernageomin.cl>.

Suazo, G., Fourie, A., and Doherty, J. (2016a). “Experimental Investigation on Propagation and Transmission of Compressional Stress Waves in Cemented Paste Backfill.” *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 143(3).

Suazo, G., Fourie, A., Doherty, J., and Hasan, A. (2016b). “Effects of confining stress, density and initial static shear stress on the cyclic shear response of fine-grained unclassified tailings.” *Géotechnique*, 66(5), 401–412.

Villavicencio, G., Breul, P., Espinace, R., and Valenzuela, P. (2012). “Control de compactación con penetrómetro ligero en tranques de relaves, considerando su variabilidad material y estructural.” *Revista de la Construccion*, 11(1), 119–133.

Villavicencio, G., Espinace, R., Palma, J., Fourie, A., and Valenzuela, P. (2014). “Failures of sand tailings dams in a highly seismic country.” *Canadian Geotechnical Journal*, 51(4), 449–464.