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Monotonic and cyclic behavior of thickened copper tailings

Comportement monotone et cyclique de résidus de cuivre épaissis

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ABSTRACT: This paper presents the results of a series of drained and undrained monotonic and cyclic triaxial tests, as well as resonant column and cyclic torsion tests carried out on samples of thickened tailings from a copper mine in operation in northern Chile. Samples were remoulded at the in-situ density, with the aim of characterizing the mechanical behavior and to obtain the degradation curves of shear modulus and damping in a wide range of distortions. This information will allow for studying the seismic behavior of the deposit in advanced numerical models. It is observed that the cyclic resistance of the material and post- liquefaction resistance are higher than reported data for other thickened tailings, and the degradation shear modulus and damping increase curves (Silty Clay) are similar to those reported for natural non-plastic fines and sands.

KEYWORDS: thickened tailings; liquefaction, cyclic behavior.

RÉSUMÉ: Cet article présente les résultats d'une série d'essais triaxiaux monotones et cycliques drainés et non drainés, ainsi que des essais de colonne résonante et de torsion cyclique effectués sur des échantillons de résidus miniers épaissis provenant d'une mine de cuivre en exploitation dans le nord du Chili. Les échantillons ont été remaniés à la densité in-situ, dans le but de caractériser le comportement mécanique et d'obtenir les courbes de dégradation du module de cisaillement et d'amortissement dans une large gamme de distorsion angulaire. Cette information permettra d'étudier le comportement sismique du dépôt de résidus à l'aide des modèles numériques avancés. On observe que la résistance cyclique du matériau et la résistance à la liquéfaction sont plus élevées que les données rapportées par d'autres auteurs, et que le module de cisaillement de dégradation et les courbes d'incrément d'amortissement sont semblables à celles rapportés pour des sols fins non-plastiques et pour des sables.

MOTS-CLÉS : résidus épaissis, liquéfaction, comportement cyclique.

1 INTRODUCTION

Over the last two decades, the world-wide demand for copper has been rising steadily. Hence, some of the large copper recovery operations (>100,000 tonnes per day) in Chile, mainly located in the high Andes Mountains of the Atacama Desert, are looking to expand their production. Although rich in minerals, the Atacama Desert is extremely dry.

Typically, after the mineral recovering process 99% of the rock extracted from the mine is waste in the form of slurry tailings containing about 50% of water in weight. Copper tailings are typically a mix of sand and non-plastic silt. The most common tailings management method is the hydraulic discharge of the slurry into a storage facility confined by dams, containing loose and saturated tailings. Under these conditions, earthquakes could trigger tailings liquefaction and there is a well-documented history of earthquake-induced tailings dam failures (Dobry and Alvarez 1967, Villavicencio et al. 2013). Liquefaction is the second cause of tailings dams failures, 90% occurs in active mines, United States and Chile lead the ranking of reported cases (Rico et al. 2008).

The optimization of tailings dams operation deals mainly with maximizing the storage volume, minimize the dam high and volume, and maximize water recovery from the pond in order to minimize the amount of fresh water required. However, water storage in open ponds is subjected to seepage and high evaporation rates. To avoid high water losses in the deposit, an alternative is to recover more water at the process plant by thickening the tailings up to a dense slurry with almost no free water, but still able to flow into the deposit. This method is well-known as the Thickening Tailings Deposition (TTD) and has been originally proposed by Robinsky (1982) in Canada. Thickening is assessed by flocculation and accelerated sedimentation in a mechanical equipment. The thickened slurry is then hydraulically deposited and forms cones of soft slopes of around 2 to 4% (Robinsky 1999). Thus, the gain in process water recovery is made at the thickening plant, before tailings discharge. Since free water is almost null in the deposit, there is almost no sedimentation neither segregation, so the water discharged is hardly recoverable and water is lost by evaporation, seepage and retention into the tailings voids.

Advantages of this method could be: improvement of slope stability, reduction of the confining dam height, deposited volume, and liquefaction potential (Robinsky 1999). However, even at the shrinkage limit, typical sandy-silt copper tailings could stay quite loose and contractive (Ishihara et al. 1980, Cifuentes & Verdugo 2007, Santos 2011). Therefore, to ensure seismic stability it is necessary to evaluate case by case the vulnerability of flow failure and/or cyclic mobility.

TTD projects in the world have been mainly developed in low to medium tailings rate production mines located in regions with low seismic hazards (Jewell et al. 2002). However, during the past 10 years, large mines in Chile have been interested in TTD in order to save water and today some large projects are starting operation. Hence, there is still no reported cases of the seismic response and experimental data related to the mechanical properties of the in-situ material is quite limited. Moreover, predictive methods for liquefaction potential evaluation and engineering designs are in general quite simplified (Poulos et al. 1985, Palma et al. 2007). Consequently, there is a need of a more sophisticated analysis to predict the seismic behavior, including undrained and dynamic behavior of the tailings.

This paper describes an accurate experimental program for material characterization, in order to obtain monotonic and cyclic properties. These properties are used for constitutive model calibration implemented in an advanced numerical FEM model that considers cyclic behavior. The results intend to be used in future analysis of seismic stability related to large thickened tailings deposits.

2 EXPERIMENTAL PROGRAM

The material was taken from a thickened tailing operation located in Atacama Desert. In particular, the material extraction zone was near to discharge. A total of 8 bucket with 25 liters of storage each one were collected from that point. Tailings on this area are discharged with a 65% of solids (weight of solids / total weight), in situ data of surface tailings shows an average dry density of 15.2 kN/m^3, obtained from 20 sand cone tests (ASTM D1556).

Experimental laboratory program started carrying out grain size distribution test to four different samples. Figure 1 shows the results, according to ASTM D2487 standard, the tailings classify as clayey silt (CL-ML), Plastic Index of 6, Liquid Limit of 24, fines content of 65 to 75% (finer than 0.074 mm) and specific gravity (Gs) of 2.76. From Standard Proctor compaction curve, the maximum dry density (γ_d^{max}) was 17.3 kN/m^3 and an optimum water content of 16%.

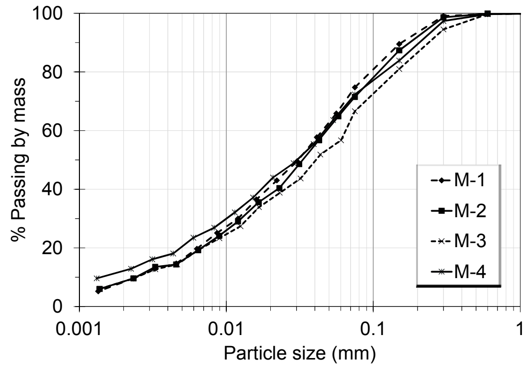

Figure 1. Grain size distribution

Sample preparation for cilyndrical samples preparation was achieved by wet-tamping at a dry density of 15.2 kN/m^3, corresponding to the shrinkage limit and a medium loose state of 88% of the maximum dry density from Standard Proctor.

Cylindrical samples were 100 mm height and 50 mm in diameter for monotonic tests, and 140 mm height and 70 mm in diameter for cyclic tests. Each sample was prepared by five compacted layers with a water content of 18% in a rigid mold covered by a latex membrane. Samples were saturated first with CO_2 gas and later with de-aired water up to a Skempton parameter (B) of at least 95%.

2.1 Monotonic tests

Strain controlled isotropically consolidated drained (TMD) and undrained (TMU) triaxial monotonic compression tests at effective confining pressures (σ'_3) of 100, 300 and 500 kPa were performed using a vertical displacement rate of 0.05 mm/min. Deviatoric (q) and effective mean (p') stresses are defined as: $q=\sigma'_1-\sigma'_3$ and $p'=(\sigma'_1+2\sigma'_3)/3$. Figure 2 presents effective stress and strain paths, and the common critical state line (CSL) for drained and undrained tests. As expected, medium loose tailings behaved with excess pore pressure in the range of 20 to 30% of the total mean stress (Figure 3). Figure 4 shows the relation between the undrained shear strength (Su=q/2) and σ'_3, with a unique ratio $Su/\sigma'_3=0.56$ at critical state.

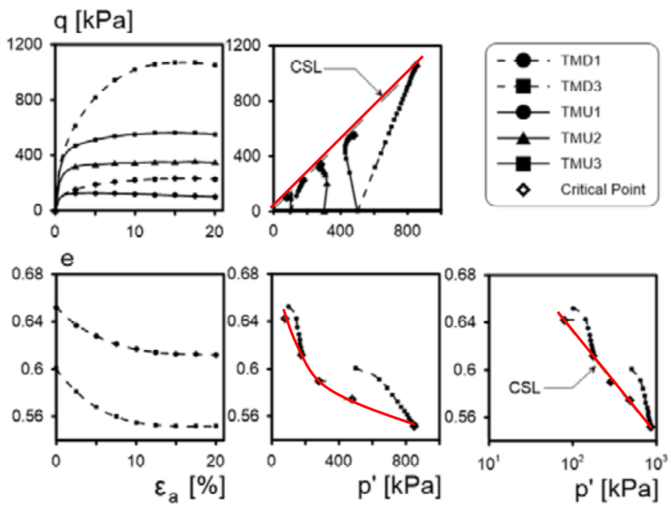

Figure 2. Monotonic triaxial compression tests and critical state analysis

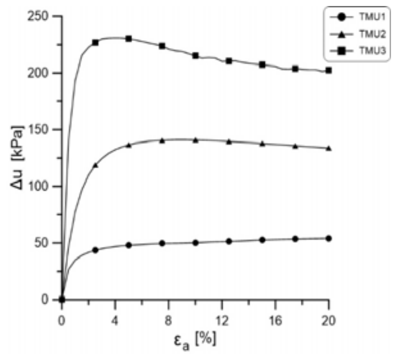

Figure 3. Excess pore pressure in monotonic undrained triaxial tests

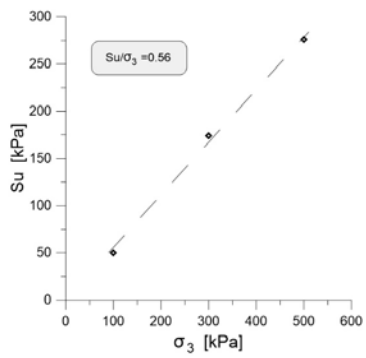

Figure 4. Undrained shear strength in triaxial tests

2.2 Cyclic tests

2.2.1 Cyclic liquefaction triaxial test

Cyclic extension-compression undrained triaxial tests (TCU) were carried out controlling the deviatoric stress amplitude at constant load frequency of 0.05 Hz. The imposed cyclic load was chosen for a range of Cyclic Shear Ratio ($CSR=q/(2\sigma'_3)$), in order to obtain data allowing to represent the response in a typical range of number of cycles for liquefaction between 10 and 100. Figure 5 shows a typical result of a TCU test up to liquefaction at cycle number 24, for a liquefaction criteria based on 10% of axial strain in double amplitude. Figure 6 presents the results for all TCU tests. Characteristic CSR values associated to 20 cycles for liquefaction typically used a simplified method (Seed, 1987) is 0.3.

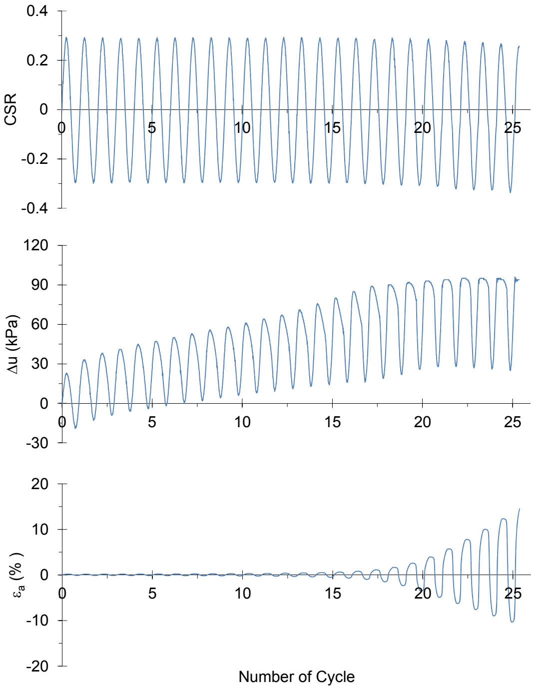

Figure 5. Cyclic undrained test result for σ’$_3$=100 kPa and CSR=0.28

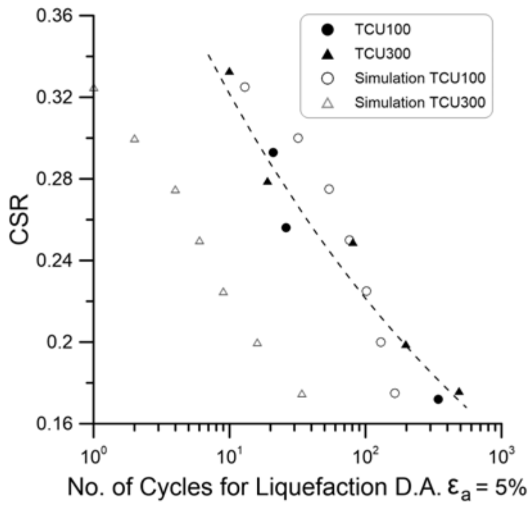

Figure 6. Undrained cyclic resistance in TCU tests

2.2.2 Cyclic degradation tests

Cyclic stiffness degradation and hysteretic damping of the thickened tailings samples were measured in cyclic shear tests at different confinement (100 and 300 kPa) and very low to large shear strains. Tests performed include resonant column (RC), torsional shear (TS) and drained cyclic triaxial (TCD). Shear strain ranges used were 10^{-4} to 10^{-2} for RC, 10^{-2} to 10^{-1} for TS and larger than 10^{-1} for TCD. According to ASTM D3999 and D4015, shear stiffness (G) and shear strain (γ) were obtained after 40 cycles. At low strain (γ=10^{-3}) the maximum shear stiffness (Go) takes values of 130 and 207 MPa at confinements of 100 and 300 kPa, respectively. These values are typical for medium loose silty sands. Normalized stiffness (G/Go) and damping (D) values are presented in Figure 7, where both results are compared with the data published by Seed and Idriss (1970) for sands, and Vucetic and Dobry (1991) for non-plastic fine soils. There is a good agreement between both curves and results obtained.

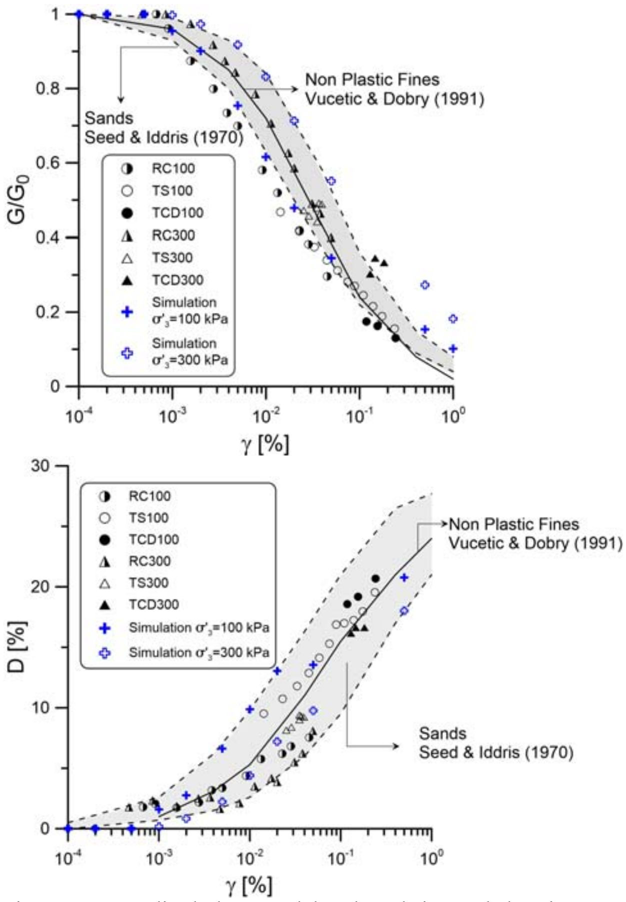

Figure 7. Normalized shear modulus degradation and damping

3 NUMERICAL MODELING

The Ecole Centrale Paris (Hujeux, 1985) elasto-plastic multi-mechanism model was used because its ability to reproduce large range of deformation and cyclic behavior. This effective-stress model can take into account the soil behavior in a large range of deformations. The representation of all irreversible phenomena is made by four coupled elementary plastic mechanisms: three plane-strain deviatoric plastic deformation mechanisms in three orthogonal planes, and an isotropic one. The model uses a Coulomb-type failure criterion and the critical-state concept. The evolution of hardening is based on the plastic strain (deviatoric and volumetric strains for the deviatoric mechanisms, and volumetric strain for the isotropic one). A kinematical hardening, based on the state variables at the last load reverse, is used to take into account the cyclic behavior. The soil behavior is decomposed into pseudo-elastic, hysteretic, and mobilized domains. Calibrated material parameters are displayed in Table 1. Figures 6, 7 and 8 present the calibration of different tests at 100 and 300 kPa of initial confinement.

Table 1: Calibrated parameters of the ECP model.

Parameter name	*Value*	*Meaning*
G_{ref} (MPa)	192.5	Reference shear modulus
K_{ref} (MPa)	280.6	Reference bulk modulus
n_e	0.43	Degree of non-linearity for elastic modulus evolution with confinement
p'_{ref} (MPa)	1.0	Reference confinement for non-linear elasticity
$\varphi_{pp}{}^{\circ}$	30.5	Friction angle at critical state
$\psi_c{}^{\circ}$	30	Characteristic angle (limit

		between contractive and dilative behavior)
β	30.8	Plastic compressibility (related to density's hardening)
d	2.1	Distance between virgin isotropic consolidation line (ICL) and critical state line (CSL)
b	0.45	Yield surface shape factor ($b=0$ is Mohr-Coulomb type and $b=1$ is Cam-Clay type)
p_{c0}' (kPa)	100	Projection of initial void ratio on CSL
a_m a_{cyc}	2.4×10^{-3} 1.1×10^{-4}	Hardening coefficients for shear mechanisms (monotonous and cyclic)
c_m c_{cyc}	1×10^{-3} 5×10^{-3}	Hardening coefficients for isotropic mechanism (monotonous and cyclic)

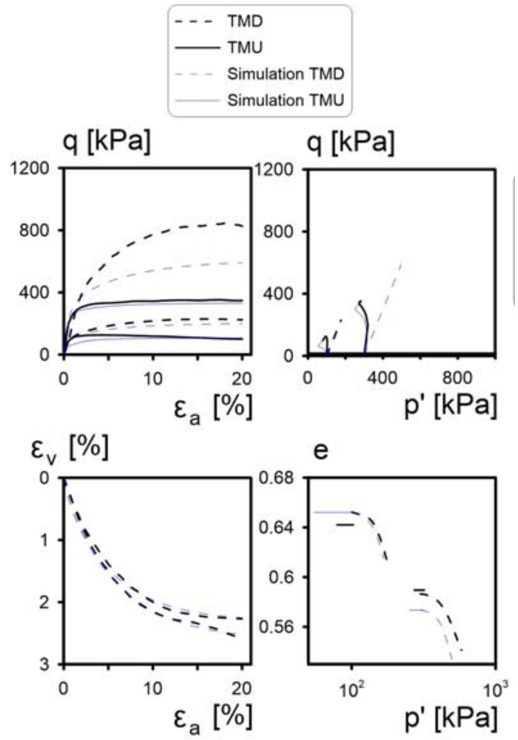

Figure 8. Monotonic tests simulations

In general terms, monotonic and drained cyclic test at 100 and 300 kPa are satisfactorily reproduced by parameters presented in Table 1. Nevertheless, undrained cyclic behavior shown in Figure 6 is only reasonably reproduced at 100 kPa. Indeed, the model tends to overestimate the effect of confinement in the number of cycles to reach liquefaction. A different set of parameters at 300 kPa is being calibrated to correct this effect.

4 CONCLUSIONS

Experimental program performed allowed to characterize the monotonic and cyclic thickened tailings behavior at the in situ characteristic dry density conditions (surface deposited tailings). The material presented a critical state characterized by a straight line in e-log(p') plane and a Mohr-Coulomb residual strength with a cohesion of 10 kPa and friction angle of 30 degrees.

Undrained strength ratio Su/σ'3 resulted of 0.56 and liquefaction resistance of 0.3 using Seed (1987) method. Both measures are higher if are compared with others tailings tests densified by drying (Cifuentes and Verdugo 2007, Santos 2011, Osorio 2009). This, could be explained by the high amount of fines (Puma et al 2016), which would allow high density by shrinkage drying.

In relation to degradation curves, due to its low plastic index, the material behaves similar to classical reported clean sands and non-plastic fines along the whole shear strain range.

The calibration of the ECP model shows a satisfactorily adjustment for both, monotonic and cyclic paths. Because of this, it is expected to be used for future researches involving seismic simulation to assess possible failure triggered by cyclic mobility or liquefaction.

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