PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

HYDROMECHANICAL CHARACTERIZATION OF GRANULAR MATERIALS FROM COPPER MINING WASTE

DANIELA PUMA CONTRERAS

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
CARLOS ENRIQUE OVALLE ORTEGA

Santiago de Chile, August, 2017

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To my parents

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Firstly, I wish to thank my parents for their unconditional support throughout my whole life. Also, to my aunts, uncles, cousins, and brother for always accompanying me.

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ABSTRACT

The present research is a study of granular materials originating from copper mining waste from a geotechnical point of view. This thesis has two independent main chapters: (1) an experimental study on tailings and (2) a study on a heap leaching material. Chapter 1 deals with the effect of sample preparation method on the undrained, cyclic and dynamic behavior of thickened tailings. An extensive testing program was carried out; this included undrained monotonic and cyclic triaxial, torsional shear and resonant column test performed on three different preparation techniques. The results presented consist in critical state lines, undrained and liquefaction resistance, shear modulus, and damping curves. The main conclusions are that undrained cyclic resistance depends on the sample preparation method, while the critical state does not. In addition, shear modulus degradation is quite similar to reported curves for sands and non-plastic fines, and a slight effect of sample preparation exists only for small strains.

On the other hand, Chapter 2 is an experimental and numerical study of hydraulical characterization and sensitivity parameter analysis on a heap leaching material. The characterization consisted in performing tests to obtain the soil-water characteristic curve (SWCC), as well as standard tests as grain size distribution and saturated hydraulic conductivity. Also, a 1D column of the leach pad was modeled using a specific model for unsaturated soils. With the purpose of analyzing the key parameters of the model, a sensitivity analysis was carried out. The main results included three hystereticel curves at different initial porosities, and the key parameters found are the irrigation rate and the shape of the water retention curve; finally, the permeability does not affect the saturation process time for values presented on the field.

Keywords: waste mining, laboratory tests, liquefaction, numerical modelling, partial saturation.

RESUMEN

La presente investigación es un estudio acerca de materiales granulares provenientes de desechos mineros del cobre con un enfoque geotécnico. Esta tesis contiene dos capítulos independientes: (1) un estudio experimental de relaves y (2) un estudio de material de pilas de lixiviación. El capítulo 1 trata del efecto del método de preparación de probetas sobre el comportamiento no drenado, cíclico y dinámico de relaves espesados. Un amplio programa de ensayos fue realizado, este incluyó ensayos triaxiales no drenados mońotonos y cíclicos, torque cíclico y columna resonante para tres diferentes técnicas de preparación. Los resultados consisten en líneas de estado crítico, curvas de resistencia a la licuación, y curvas de amortiguamiento y degradación de la rigidez. Las principales conclusiones son que la resistencia a la licuación depende del método de preparación de muestra, a diferencia del estado crítico. Además, la degradación del módulo de corte es similar a las curvas reportadas para arenas y finos no plásticos, y se aprecia un leve efecto a pequeñas deformaciones.

El capítulo 2 es un estudio experimental y numérico de caracterización hidráulica y sensibilidad de parámetros de un material de pilas de lixiviación. La caracterización consistió en realizar ensayos para obtener la curva característica agua-suelo, así como también ensayos de granulometría y conductividad hidráulica. Además, una columna unidimensional de pila fue modelada como un permeámetro y se usó un modelo específico para suelos parcialmente saturados. Para analizar los parametros críticos del modelo se realizó un análisis de sensibilidad. Los principales resultados encontrados fueros tres curvas histeréticas a distinta porosidad inicial, y como parámetros críticos, la tasa de irrigación y la forma de la curva de retención, finalmente se obtuvo que un cambio en la permeabilidad no afecta el tiempo de saturación del material para los valores presentados en terreno.

Palabras Claves: desechos mineros, ensayos de laboratorio, licuefacción, modelación numérica, saturación parcial.

1. EFFECT OF SAMPLE PREPARATION ON MONOTONIC, CYCLIC AND DYNAMIC PROPERTIES OF THICKENED COPPER TAILINGS

1.1. Introduction

Chapter 1 is divided in two main parts. First, an introduction and, secondly, a copy of the scientific article submitted to Canadian Geotechnical Journal on June 14th 2017. The introduction contains the motivation and objectives of the study, as well as details of the methodology that are not included in the article.

1.1.1. Motivation

Worlwide, 20 Mton of refined copper are produced annually (ICSG, 2017). Around 99 times of this significant volume is waste materials which must be managed and deposited in a environmentally safe condition. A part of the ore production comes from copper sulfurous, and the waste generated from this process is called tailings.

Tailings deposits requires a containing dam, which could be built with tailings sand or with granular fills (e.g. rockfills). Into the deposit, tailings are hydraulically discharged, forming a sedimentation pond. This methodology generates a very loose and saturated material. A number of failures have been registered in this kind of structures, Berghe et al. (2011) reported that 4 of 3500 tailings dams experience considerable damage each year. Furthermore, Azam & Li (2010) estimated that failures of the last century correspond to a 1.2% of the existent tailings. Moreover, Rico et al. (2008) noted that the primary cause of the failures on tailings, and the second for all kinds of dams worldwide, is the liquefaction phenomenon.

Currently, Chile has 696 tailings facilities registered (SERNAGEOMIN, 2016) and a long record of failures. Dam failures records indicate that a 12.3% of the total belong to Chile, having the second place in the list only behind USA (Rico et al., 2008). Failures in El Cobre Viejo, El Cobre Nuevo, Cerro Negro No. 4, Barahona, among others, have been broadly reported in the literature (Villavicencio et al., 2013; Troncoso et al., 1993; Castro & Troncoso, 1989). Most of them occurred because of they were constructed with the upstream method (today prohibited for legislation) and the large magnitude of its seismic events.

Recently, some mining operation in Chile have implemented new techniques, in particular, the use of Thickened Tailings Disposal (TTD). Worldwide, the use of this kind of technology has also grown; Davis (2011) shows that in 2010, 90 new facilities were built, stands out the TTD method with a presence of around 50.

Up to now, few studies have investigated the seismic behavior of TTD deposits (Fourie, 2006). Experimental data on cyclic and dynamic properties of thickened tailings are still quite scarce, and only a few studies about this issue has been reported (Poulos et al., 1985; Seddon, 2007; Cifuentes & Verdugo, 2009; Verdugo & Santos, 2009; Osorio, 2009; Al-Tarhouni et al., 2011; Daliri et al., 2014; Urbano et al., 2017). Also, data are difficult to compare because different authors have used different methods to prepare thickened tailings samples.

In regards to undrained cyclic resistance, some studies on fine soils and sands have suggested that it depends on the sample preparation method. In general, for a given dry density, tamping methods exhibit a greater cyclic resistance than samples prepared by pluviation (Mulilis et al., 1977; Miura, 1982; Bradshaw & Baxter, 2007; Sze & Yang, 2013). Concerning dynamic properties, few works have presented shear modulus degradation and damping dynamic properties of sand tailings and non-plastic silt tailings (Rojas-González & Lewis, 1985; Troncoso & Verdugo, 1985; James et al., 2011; Zhao et al., 2014). However, as far as we know, there are no studies reported on thickened tailings.

This research is motivated by the lack of experimental data and the requirement of accurate predictions of the seismic behavior of thickened tailings disposal. Five non-segregating copper tailings were tested using three different preparation methods: Wet Tamping (WT), Air Dried (AD) and Slurry (SL). In addition, some results are present to understand better the undrained behavior of thickened tailings densified at its shrinkage limit. The results will contribute to the study of the dynamic stability analysis of TTD deposits in high-risk seismic areas where the methodology has been growing recently, particularly for large mining projects in the Andes Mountains.

1.1.2. Objectives

- **General objective**

  The aim of the present investigation is to study the effect of sample preparation method on the monotonic, cyclic and dynamic behavior of several thickened tailings.

- **Specific objectives**
  - Geotechnical characerization of five thickened tailings.
  - Prepare tailings samples at the in-situ density using three different preparation methods (Wet Tamping, Air Dried, and Slurry).
  - Evaluate the monotonic undrained behavior at large deformations (Critical State) and liquefaction resistance through undrainded cyclic shear tests.
  - Obtain the dynamic properties evolution by cyclic stiffness degradation and damping tests.

1.1.3. Methodology

The methodology used for achieving the aims proposed was an exhaustive experimental campaign. It consisted of an extensive testing program on a thickened tailing material. This material was collected from a thickened tailing deposit, in particular, from the discharge zone; the notation used in Chapter 1 for this material is EU.

To analyze the monotonic behavior undrained triaxial tests were performed. While, to study the cyclic behavior liquefaction resistance, resonant column, torsional shear, and drained cyclic triaxial tests were carried out. For this purpose, two equipment were used: the cyclic triaxial and the resonant column apparatus.

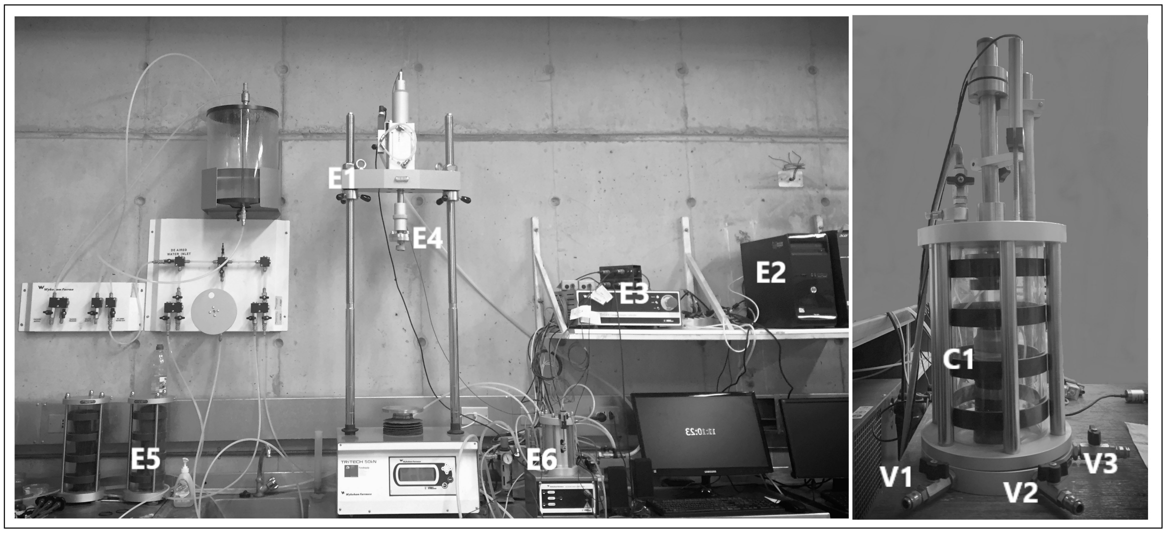

Figure 1.1. Cyclic triaxial test equipment

Cyclic triaxial equipment is presented in Figure 1.1; this is used for performing such as monotonic triaxial as cyclic triaxial tests. It consists of a load frame (E1) where is placed the main cell with the sample (C1), a control system (E2), which is in charged of to control the cell pressure (σ'_c), back pressure (σ'_{bp}), piston displacement, back pressure valve and receive and calculate the different data acquired for the data acquisition system (E3).

The piston (E4) applies an axial force to the sample that depending on the kind of test, can only be a loading mode (monotonic) or loading and unloading, if the test is cyclic. Moreover, the cell use three different valves for connecting with the other components. The first one (V1) is used for connecting with the balloon (E5) that controls the cell pressure, the second one (V2) connects with the pore pressure sensor. Finally, the last valve (V3) connects with the back pressure sensor and allows the water flow inside and outside of the sample, this flow passes to a volumetric instrument (E6), where it is registered.

Moreover, the figure 1.2 shows part of the resonant column equipment. The set-up is composed of a cell, the sample, the torque actuator, and transducers. This apparatus is capable of measuring small strain levels (as low as $10^{-4}\%$), and it is used to perform the resonant column and torsional shear tests.

Its working principle consists in to apply a variable amplitude regarding the voltage; this amplitude is transmitted to the sample by a torque movement produced by the motor, while the bottom's sample is fixed to the apparatus.

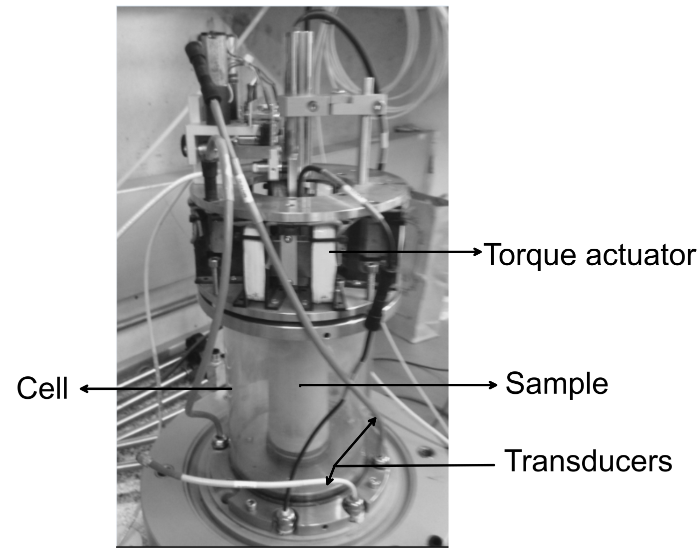

Figure 1.2. Resonant column equipment

All tests have as first stage standard before of the change on the confining conditions, a process whereby it passed a flow of CO_2. This process is used for filling with gas all voids that are occupied by air, because of CO_2 is more soluble in water than air. Later, it passed a flow of distilled water, until to get a volume of outflow greater than 40% of the sample volume. After this, start the saturation process, whereby, the cell and the back pressure increase keeping the same difference of pressures that at set-up conditions (20 kPa).

$$B = \frac{\Delta u}{\Delta \sigma'_c} \tag{1.1}$$

The proceeding used to ensure that the sample is effectively at saturated condition is a B-value test. This test consists in increase the cell pressure, while the water valve (V3) is closed. So, if the increase of pore pressure (Δu) resulting of the increment in the cell pressure ($\Delta\sigma'_c$), produces a B-value equal or greater than 95%, the sample is considered saturated and ready for the consolidation process.

The consolidation process is also standard for all tests and consists in applying a pressure of consolidation ($\sigma'_3 = \sigma'_c - \sigma'_{bp}$) wanted. And after this, the water valve (V3) remains open, the time of duration associated with this process is 24 hours because of the low permeability related to this material. Afterward, the curve volumetric water change versus time, reaches a horizontal asymptote.

The following subsections describe the different tests carried out in both apparatus.

1.1.3.1. Undrained monotonic triaxial

Test performed according to ASTM D4767-04 (2004), after saturation and consolidation process, the monotonic test starts at controlled strain rate of 0.15 mm/min for all samples. This procedure is running until to reach a strain of 20%, in other words, when it registered a displacement of 2 cm o more in a sample of 10 cm height. During the test the consolidation pressure (σ'_3) is constant, and the variables recorded are the pore pressure, axial displacement, and the force applied by the piston. The water valve is closed in all process, then, the volumetric water content of the sample does not change.

1.1.3.2. Undrained cyclic triaxial

Test performed according to ASTM D5311-92 (1992), consists in to choose a Cyclic Shear Ratio (CSR) for applying to the sample while the water valve is closed. The CSR selected is the constant amplitude strength applied to the sample, in loading and unloading mode.

$$CSR = \frac{q}{2\sigma'_3} \tag{1.2}$$

The process of loading and unloading produces an increment in the pore pressure; when the B-value associated with this is equal or greater than 95%, the test is considered completed, and the number of cycles related to this condition is registered.

1.1.3.3. Drained cyclic triaxial

Test performed according to ASTM D3999-91 (1991), consists in to apply a defined shear strength by a loading and unloading process at a frequency of 0.005 Hz. This frequency is the lower limit allowed for the equipment, the choice of a low frequency is to avoid a change in the pore pressure throughout the test.

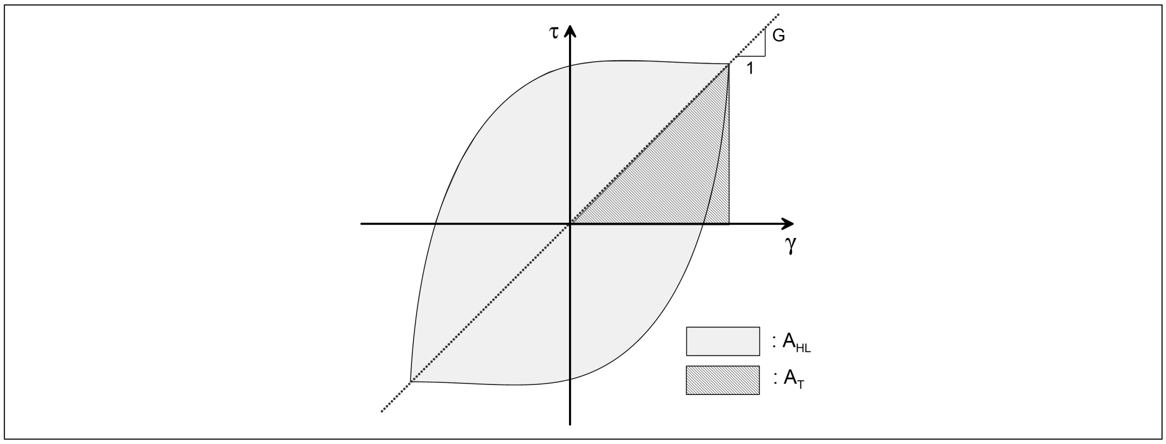

Figure 1.3. Scheme of hysteresis loop

The cyclic shear test has a duration of 40 cycles, in the last one, different properties such as shear (G) and elastic modulus (E), damping (D), and shear strain (γ) are evaluated. Figure 1.3 shows a scheme of the hysteresis loop in the plane τ versus γ. It is direct to calculate G and γ, and Equation 1.3 explain how to get the damping value.

$$D = \frac{A_{HL}}{4\pi A_T} * 100[\%] \quad (1.3)$$

1.1.3.4. Resonant column

Test performed according to ASTM D4015-07 (2007), this test uses as basic principle the propagation of elastic waves, with the assumption that the propagation is produced in an elastic, isotropic and homogeneous material. Firstly, a small amplitude is chosen, later a frequency range is sampled until to get the resonant frequency (f_r). When it occurs, a graph such as it showed in Figure 1.4 exhibits a peak of shear strain, the value related is called γ_{max}. Also are recorded the frequencies associated to a strain of $0.707\gamma_{max}$, which are called f_1 and f_2.

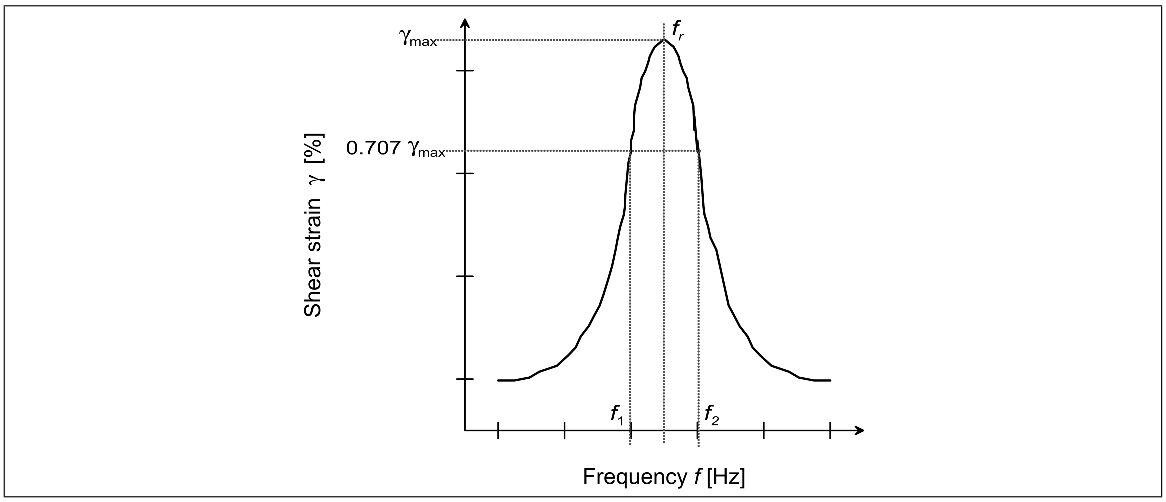

Figure 1.4. Scheme of parameter calculation in resonant column

To calculate the damping associated with that strain Equation 1.4 is used, with the values recorded previously. Furthermore, to calculate the shear modulus is necessary to know the shear wave velocity (V_s). Thus, it is used the Equation 1.5, where I is the sample's polar mass moment of inertia, I_o is the actuator polar mass moment of inertia, and L is the sample height. After, the shear modulus results from the use of the Equation 1.6, where ρ is the sample density.

$$D = \frac{f_2 - f_1}{f_r} * 100[\%] \quad (1.4)$$

$$\frac{I}{I_o} = \frac{2\pi f_r L}{V_s} \tan\left(\frac{2\pi f_r L}{V_s}\right) \quad (1.5)$$

$$G = \rho V_s^2 \quad (1.6)$$

The process described above is repeated at increasing amplitude up to reach a shear strains of about 10^{-2} %.

1.1.3.5. Torsional shear

The same sample used here is the same sample tested in the resonant column test. The first amplitude used in the current test, corresponding to the last one recorded for the resonant column. For this test, a single low frequency must be chosen, after, 20 cycles are performed to an equivalent torque associated to the amplitude. If the cycles are stables, the shear modulus, damping, and shear strain can be calculated with the same procedure used for drained cyclic triaxial test. After, the amplitude can be increased up to reach the maximum torque able to be imposed or up to the cycle been inestables.

1.1.4. Conclusions and future work

The purpose of the current study was to determine the effect of sample preparation on the monotonic and cyclic behavior of copper thickened tailings. With this aim, a material originating from a thickened tailing deposit was analyzed, which was collected directly from the discharge point. The material was tested by monotonic and cyclic tests for an accurate characterization. These tests were carried out on three different sample preparation methods. Furthermore, results were compared with similar materials reported in the literature. The results of this study indicate that:

- CSL and undrained strength ratio under monotonic shearing do not depend the sample preparation method.
- Undrained cyclic behaviour of EU material depends on the sample preparation method, and presents a liquefaction resistance at 20 cycle (CSR_{20}) of 0.27 for WT and 0.38 for AD. However, thickened tailings studied by other authors do not show that kind of dependency, therefore, this effect should be studied case by case.
- Results of different tailings materials show an increase of Su/σ'_3 with the fines content. This could be attributed to the drying procedure, where the densification reached by drying and shrinkage increases with the presence of fines.
- Normalized shear modulus (G/Go) and damping (D) curves for EU material present a behavior comparable with curves reported by literature for sands and non-plastic fine soils.
- The comparison of preparation methods reveals that WT results in a Go 35% higher than SL at 100 kPa of confining pressure. Nevertheless, at shear strains greater than 0.1%, results about G and D are similar for the 3 different preparation methods. However, further tests under different conditions (preparation method, density, confining pressure) are required to consolidate these findings.

In order to consolidate, improve and use the current findings in practice, it is recommended as further work the following:

- Increase the cyclic database, particularly, to add results from the resonant column and torsional shear tests for AD samples. And, carried out these same tests for SL samples at different confining pressures.
- To conduct a numerical modeling analysis for a thickened tailing disposal under dynamic loading conditions, using different initial properties in accordance with the results of different sample preparation methods obtained. And to study its dynamic stability for each case establishing the relevance of the sample preparation method on the TTD dynamic response.

The next section correspond to the article submitted to Canadian Geotechnical Journal. It does not have contents changes, only was adapted to the thesis format.

1.2. Effect of sample preparation on monotonic, cyclic and dynamic properties of thickened copper tailings

Abstract

The thickened tailing disposal (TTD) method was developed by Robinsky (1975), and it has applications in small to medium mining operations. TTD considers a thickening process before disposal to produce a dense pulp with almost no free water; which is exposed to surface drying and allowed to reach their shrinkage limit. Recently, TTD has also been proposed in copper mines with high production rates and located in highly seismic areas. However, data on cyclic and dynamic behavior are rare and it is not clear that the density reached at the shrinkage limit could provide a stable seismic condition and prevent liquefaction.

With the aim of better understanding its seismic behavior, a broad testing program was carried out on copper tailings from five TTD projects. Undrained behavior and dynamic properties in resonant column and torsional shear tests were obtained. We present results on critical state lines, undrained and liquefaction resistance, shear modulus and damping. The main conclusions are that undrained cyclic resistance depends on the sample preparation method, while critical state does not. In addition, shear modulus degradation is quite similar to reported curves for sands and non-plastic fines, and a slight effect of sample preparation exists only for small strains.

Keywords : Tailings; Laboratory tests, Liquefaction; Cyclic.

List of notation

Su	:	is the undrained shear strength
σ'_3	:	is the consolidation normal stress
σ'_1	:	is the axial stress
γ_{d_ps}	:	is the dry density related to standard proctor test
γ_{d_tx}	:	is the dry density of sample preparation
e_{prep}	:	is the void ratio of sample preparation
e_{cs}	:	is the void ratio on critical state
p'	:	is the mean stress defined as $p' = (\sigma'_1 + 2\sigma'_3)/3$
q	:	is the deviatoric stress defined as $q = \sigma'_1 - \sigma'_3$
CSR	:	is the cyclic shear ratio defined as $CSR = q/2\sigma'_3$

1.2.1. Introduction

The worldwide annual production of refined copper in 2016 was 20.2 Mton (ICSG, 2017). This results in huge amounts of waste; typically the ratio between tailings and copper produced is around 99. Moreover, estimates predict an increase in copper production and a drop in the ore grade on the reservoirs. This would generate a significant increase of the waste volumes produced annually. Therefore, the study of safe and environmentally acceptable disposal methods for tailings deposits that are getting larger is a relevant topic for the mining industry.

Over the last decades, new tailings deposition techniques have been developed to respond to challenges which include: the growing volume of incoming flow, water as a restricting resource, seismic stability , and difficulties related to the site topography. Among these techniques, the Thickened Tailings Disposal (TTD) method proposed by Robinsky (1975, 1999) stands out. TTD considers the disposal of tailings slurry (without sand/fines separation by cycloning) with reduced water content, compared to conventional tailings ponds. The advantages could be recovering more water at the process plant, reducing losses by evaporation and seepage, allowing a denser material in the deposit, reducing its total volume and, therefore, reducing the necessary confinement dam height. First, a process of water extraction through flocculation and sedimentation produces a thickened slurry with little or almost no free water. Second, the method considers the hydraulic discharge of the dense slurry into the deposit (Figure 1.5), allowing a significant reduction of segregation and sedimentation, forming a very homogenous mass of tailings deposited in gentle slopes with angles of 2 to 4% (Robinsky, 1975, 1999; Jewell & Fourie, 2006). Finally, the discharge strategy should provide large areas exposed to natural drying by evaporation, with the aim of allowing for densification by surface drying up to the material's shrinkage limit (Figure 1.6), which is typically a medium dense state depending on its fines content.

Figure 1.5. Discharge spigot of thickened tailings slurry on top of previously shrunk material

In order to ensure seismic stability and prevent lateral spreading of TTD slopes, numerical models should take into account undrained behavior and dynamic properties of the material at the in-situ material density (Fourie, 2006). Undrained behavior has been largely studied for loose conventional tailings deposits after catastrophic seismic failures by seismic liquefaction. For instance, Castro & Troncoso (1989) obtained undrained strength ratios at critical state of about $Su/\sigma'_3 = 0.08$, on tailings deposits mainly built by hydraulic filling of slurries containing large amounts of water, allowing sedimentation and the formation of ponds. This process produces very loose saturated and segregated tailings, which therefore has low undrained strength and low liquefaction resistance. On the other hand, as explained before, thickened tailings should reach a denser state compared to conventional tailings ponds. For instance, Seddon (2007) reported undrained strength ratios of 0.18 to 0.20 for TTD slopes of non-plastic and copper tailings with 67% of fines. The author also computed a post-liquefaction safety factor of 5 using a simplified stability analysis for a tailings beach slope of 4%. However, experimental data on thickened tailings are still quite scarce and only a few prior studies about this issue have been reported (Poulos et al., 1985; Seddon, 2007; Cifuentes & Verdugo, 2009; Verdugo & Santos, 2009; Osorio, 2009; Al-Tarhouni et al., 2011; Daliri et al., 2014; Urbano et al., 2017). In addition, data are difficult to compare because different authors have used different methods in order to prepare thickened tailings samples densified at the shrinkage limit, including Wet Tamping (WT), Air Dried (AD) and Slurry (SL).

Figure 1.6. TTD deposit cone, dry layers of tailings at the toe and fresh tailings at the top discharge point; no free water flows on the deposit

In regards to undrained cyclic resistance, a number of studies on fine soils and sands have suggested that the resistance depends on the sample preparation method. In general, for a given dry density, tamping methods exhibit greater cyclic resistance than samples prepared by pluviation (Mulilis et al., 1977; Miura, 1982; Bradshaw & Baxter, 2007; Sze & Yang, 2013). The explanation of this finding is that each preparation method creates a different soil fabric. Experiments on sands (Sze & Yang, 2013) and numerical results using the discrete element method (Wei & Wang, 2017) have shown that isotropic fabric has a greater undrained cyclic resistance than an anisotropic arrangement.

In regards to dynamic properties, a few studies have presented shear modulus degradation and damping dynamic properties of sand tailings and non-plastic silt tailings (Rojas-González & Lewis, 1985; Troncoso & Verdugo, 1985; James et al., 2011; Zhao et al., 2014); however, as far as we know, there are no studies reported on thickened tailings.

This research is motivated by the lack of experimental data and the requirement of accurate predictions of seismic behavior of thickened tailings deposits. The aim of this paper is to study the effect of the sample preparation method on the monotonic, cyclic and dynamic behavior of several thickened tailings. Five copper tailings were tested using three different preparation methods (WT, AD and SL) and a number of results are presented in order to better understand the undrained behavior of thickened tailings densified at their shrinkage limit. The results will contribute to the study of the dynamic stability analysis of TTD deposits in high- risk seismic areas where the methodology has been growing recently, particularly for large mining projects in the Andes Mountains.

1.2.2. Experimental testing program

This study is based on a broad testing program of monotonic, cyclic and dynamic shear tests on a material called EU, as well as on different thickened copper tailings called CO, EMM, LB, AT (see Table 1.1). Materials were collected just after the thickening process with a percent of solids (weight of solids / total weight) of about 60 to 70%. Fines content are between 52 and 72%, and geotechnical classifications are silt (ML) or silty clay

(CL-ML), in accordance with the Unified Soil Classification System. Grading and index properties are shown in Figure 1.7 and Table 1.1(a), respectively. We have also compared our results with data from the literature for copper thickened tailings with similar characteristics as reported by Cifuentes & Verdugo (2009), Verdugo & Santos (2009) and Osorio (2009). The subsequent sections describe the different methods of sample preparation used for cylindrical samples of 50 mm in diameter and 100 mm in height. For all cases, the dry density of sample preparation corresponds to the value reached at the shrinkage limit.

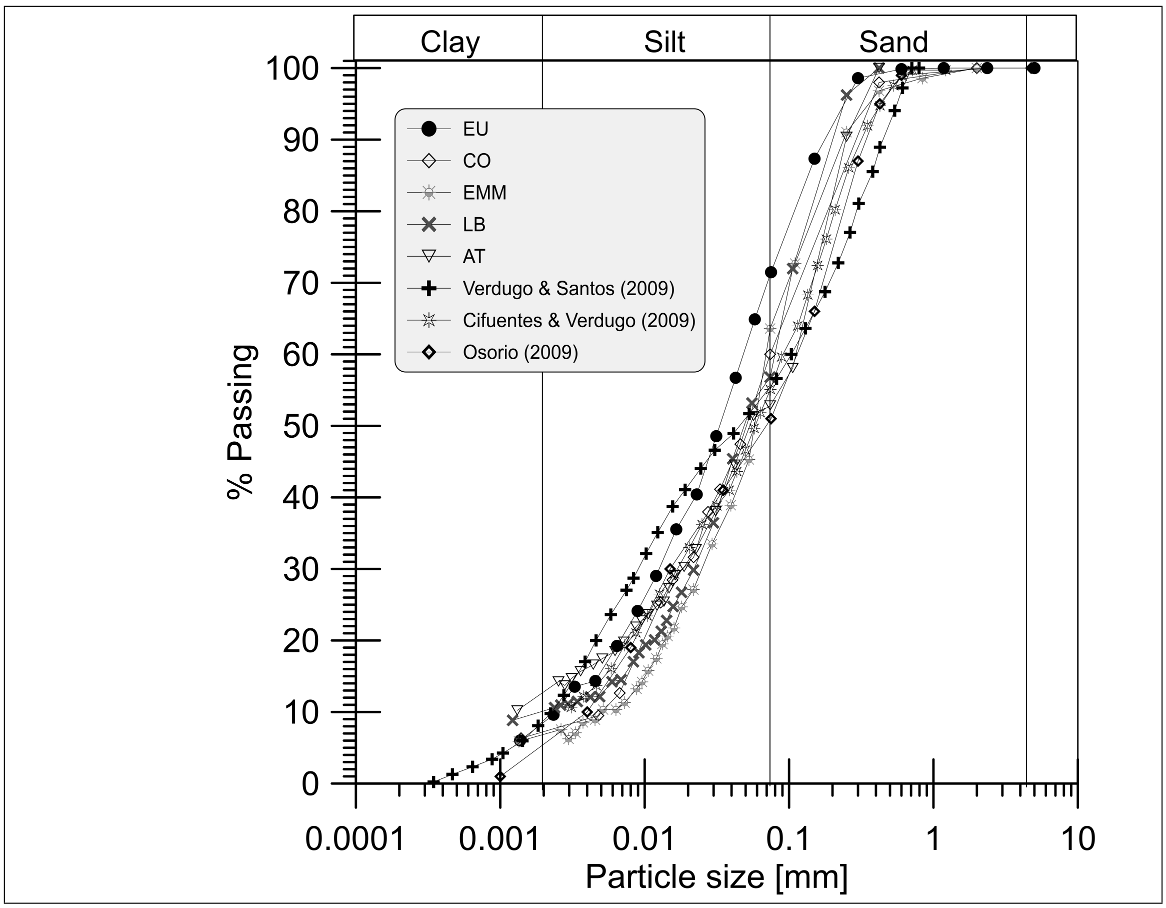

Figure 1.7. Grain size distributions

Table 1.1. Thickened tailings materials tested and literature review results

(a) Material characterization							(b) Samples for triaxial tests					
Material	Fines [%]	Gs [ ]	γ $[kN/m^3]$	LL [%]	LP [%]	USCS	Fabric	γ $[kN/m^3]$	PS [%]	e_{prep} [ ]	Su/σ_3' [ ]	RC_{20} [ ]
EU	71.50	2.76	17.36	25	19	CL-ML	AD	15.70	90	0.72	0.51	0.38
							WT	15.20	88	0.78	0.51	0.27
							SL	15.50	89	0.75	0.51	n/a
CO	60	2.71	n/a	23	19	CL-ML	AD	16.78	n/a	0.58	0.40	n/a
EMM	63.30	2.70	17.96	25	21	CL-ML	AD	15.70	87	0.69	0.37	0.22
							WT	15.70	87	0.69	0.40	n/a
LB	56.81	2.97	18.77	-	NP	ML	WT	15.11	80	0.93	0.37	0.10
AT	52.82	2.67	16.78	-	NP	ML	WT	14.32	85	0.83	0.32	0.13
Verdugo & Santos (2009)	56	2.78	19.12	18	NP	ML	AD SL	17.85	93	0.53	0.37	0.20
Cifuentes & Verdugo (2009)	55	2.75	19.22	19	NP	ML	WT AD	16.91	88	0.60	0.24	0.22
Osorio (2009)	51	2.77	n/a	18	11	ML	SL	13.83	n/a	0.96	0.31	0.21

1.2.2.1. Wet Tamping samples (WT)

Five layers of tailings with a water content of 18 to 20% were compacted in a rigid mold. The material was previously prepared by mixing dry solid tailings powder with the necessary amount of water. The dry density intends to represent the in-situ condition; in other words, this is the density achieved after contraction in the field by natural drying. For the case of material EU, the density was 15.2 kN/m^3 (88% of maximum dry density related to Standard Proctor values), according to several Sand Cone Tests carried out on the surface of the TTD deposit where EU was discharged (Urbano et al., 2017).

1.2.2.2. Air Dried samples (AD)

Samples were performed in accordance with the percent solids discharged into the TTD deposit, which was between 60 to 70% for different tailings. First, the slurry collected from the thickening process was mixed in order to get a homogenous pulp. Second, the slurry was poured into a rigid mold, where no segregation was observed and just a thin film of water appears on top. The water film was removed, and shade drying was slowly allowed during 3 months to ensure that the material reached its shrinkage limit. Water contents after this process were less than 5% and the dry densities achieved are shown in Table 1b (γ_{d_tx}). EU material reached an average dry density of 15.7 kN/m^3, corresponding to 90% of maximum dry density from Standard Proctor. Finally, samples were taken out of the molds, carved according to the sample shape and size required, and re-saturated for shearing tests.

1.2.2.3. Slurry samples (SL)

This method simulates the zones within the TTD deposit that were exposed to limited drying, so they reach the shrinkage limit but remained saturated. SL methodology is similar to AD, but the slurry poured into the rigid mold was allowed to dry for only 3 days. For instance, EU material reached an average dry density of 15.5 kN/m^3, corresponding to 89% of maximum dry density from Standard Proctor.

1.2.3. Experimental results and Discussion

For the range of materials studied, the values of maximum dry density related to its Standard Proctor test were in a range of 80 to 90%, which is typically a medium-loose to medium-dense state. We carried out monotonic and cyclic tests in triaxial and resonant column/torsional shear cells, always ensuring saturation through a Skempton parameter $B \geq 0.95$. Monotonic tests performed were triaxials isotropically consolidated drained (TMD) and undrained (TMU), under strain controlled conditions in accordance with ASTM D4767 and ASTM D7181, respectively. In order to study the liquefaction resistance, undrained cyclic triaxial tests (TCU) under load control were carried out varying the cyclic shear ratio. Dynamic properties of shear modulus degradation and damping were obtained by resonant column (RC) and torsional shear (TS) tests for small strains according to ASTM D4015 standard, and by drained cyclic triaxial (TCD) for large strains according to ASTM D3999. Results from the set of tests carried out on EU material are presented in Table 1.2, while results from other materials are summarized in Table 1(b). The notation used to define a test is the following: AA-XX-YY-ZZZ; where AA defines the material, XX the preparation sample method (AD, WT, or SL), YY the type of test (TMU, TMD, RC, TS, TCD or TCU) and ZZZ the confining pressure in kPa.

1.2.3.1. Monotonic response

Figure 1.8(a) shows Critical State Lines (CSL) on the e-log(p) plane, for different materials and different sample preparation methods; their properties are summarized in Table 1.1. Data from Cifuentes & Verdugo (2009), Verdugo & Santos (2009) and Osorio (2009) are also included for comparison. The results show that CSL does not depend on the sample preparation method or the stress path, which is a well reported result in soil mechanics (Castro, 1969; Been et al., 1991; Sadrekarimi & Olson, 2012). Figure 1.8(b) shows the undrained strength ratios Su/σ_3' at Critical State, which are linear correlations regardless of the sample preparation method. The ratios range goes from 0.32 to 0.51, which is significantly greater than the values of about 0.08 reported by Castro & Troncoso (1989) for loose tailings slimes. Furthermore, as can be seen from Figure 5, there is a correlation between the undrained strength ratios and fines content for each material. Hence, an increase in the fines content may contribute to the increase of the strength ratio, probably due to an increase of the relative densification by shrinkage drying.

Table 1.2. Summary of tests carried out on EU material

(a) Monotonic Tests					
Test	Notation	σ'_3 [kPa]	Su [kPa]	e_{prep} [ ]	e_{cs} [ ]
Monotonic undrained triaxial	EU-AD-TMU-100	100	89	0.72	0.70
	EU-AD-TMU-300	300	177	0.72	0.58
	EU-AD-TMU-500	500	280	0.72	0.55
Monotonic drained triaxial	EU-WT-TMD-50	50		0.78	0.73
	EU-WT-TMD-100	100		0.78	0.61
	EU-WT-TMD-300	300		0.78	0.54
Monotonic undrained triaxial	EU-WT-TMU-300	300	174	0.78	0.59
	EU-WT-TMU-500	500	276	0.78	0.57
Monotonic undrained triaxial	EU-SL-TMU-100	100	61	0.75	0.69
	EU-SL-TMU-300	300	159	0.75	0.62
	EU-SL-TMU-300	300	186	0.75	0.62

(b) Cyclic tests				
Test	Notation	σ'_3 [kPa]	e_{prep} [ ]	Notes
Undrained cyclic triaxial	EU-AD-TCU-100	100	0.72	CSR= 0.22; 0.31; 0.41; 0.43
	EU-AD-TCU-300	300	0.72	CSR= 0.25; 0.29; 0.32; 0.31
Drained cyclic triaxial	EU-AD-TCD-100	100	0.72	γ= 0.0764 to 0.7598 [%]
	EU-AD-TCD-300	300	0.72	γ= 0.0647 to 0.4527 [%]
Undrained cyclic triaxial	EU-WT-TCU-100	100	0.78	CSR= 0.17; 0.25; 0.29
	EU-WT-TCU-300	300	0.78	CSR= 0.17; 0.18; 0.22; 0.26; 0.30
Resonant column	EU-WT-RC-100	100	0.78	γ= 0.0007 to 0.0228 [%]
	EU-WT-RC-300	300	0.78	γ= 0.0005 to 0.0174 [%]
Torsional shear	EU-WT-TS-100	100	0.78	γ= 0.0070 to 0.1387 [%]
	EU-WT-TS-300	300	0.78	γ= 0.0057 to 0.0458 [%]
Drained cyclic triaxial	EU-WT-TCD-100	100	0.78	γ= 0.0698 to 0.2419 [%]
	EU-WT-TCD-300	300	0.78	γ=0.0577 to 0.1826 [%]
Resonant column	EU-SL-RC-100	100		γ=0.0007 to 0.0131 [%]
Torsional shear	EU-SL-TS-100	100		γ= 0.0046 to 0.2702 [%]

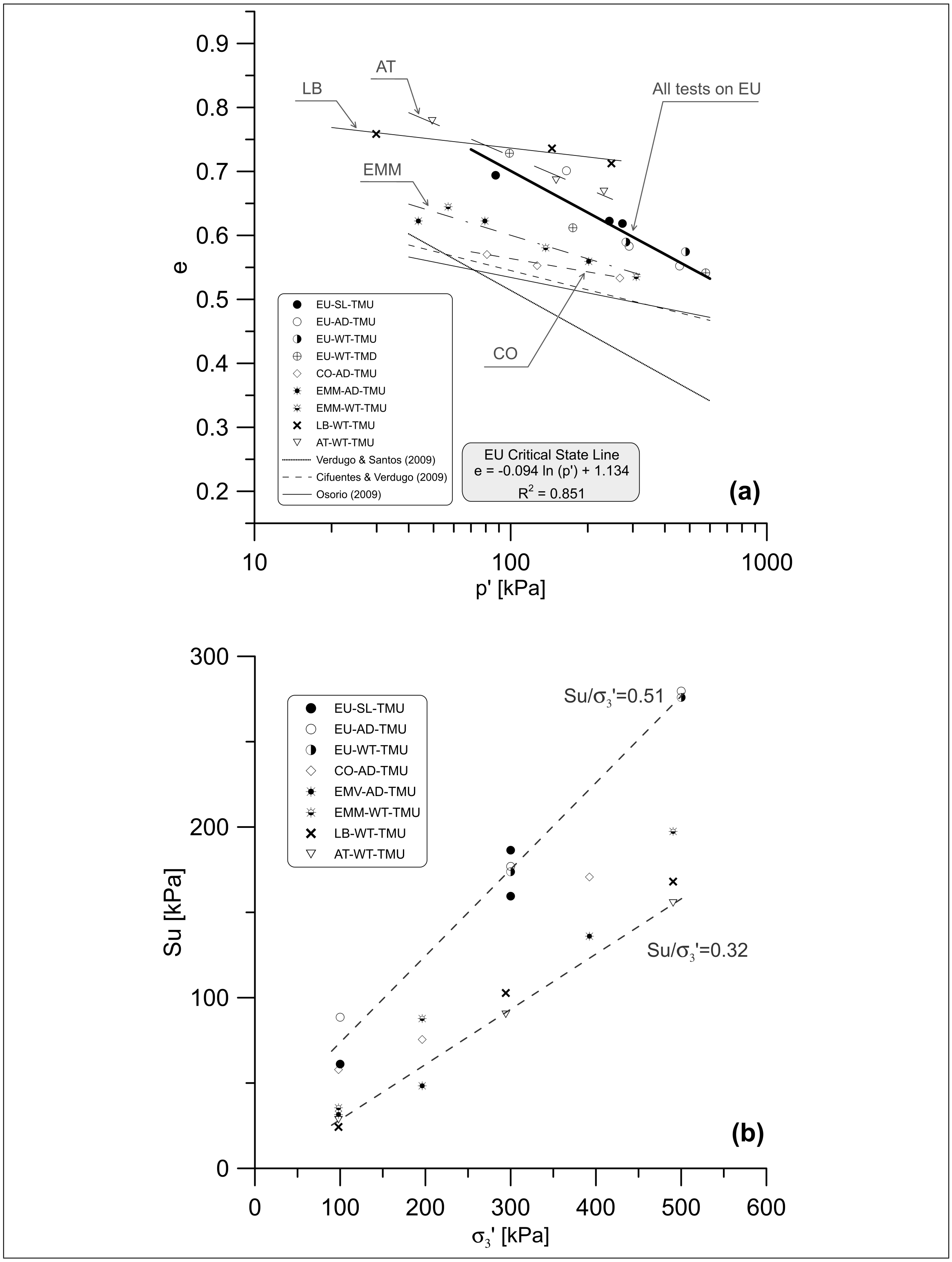

Figure 1.8. Comparison of results of critical state: (a) e-log p and (b) Undrained shear strength

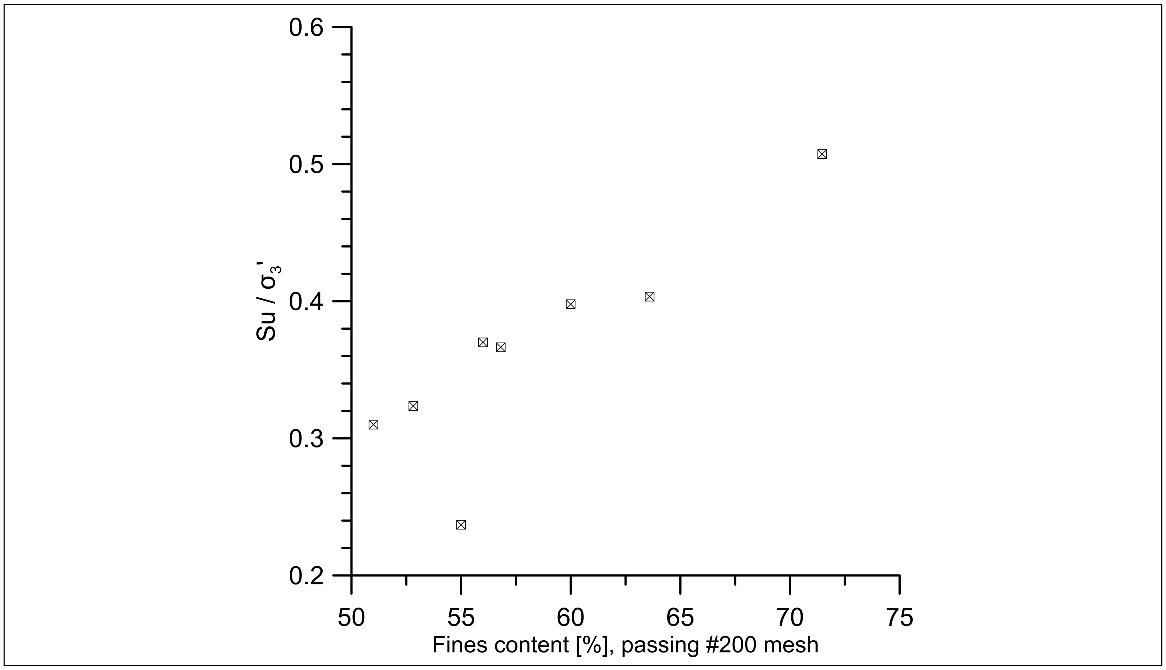

Figure 1.9. Relationship between fines content and Su/3 for all tests in Table 1(b)

1.2.3.2. Cyclic undrained response (liquefaction)

EU material presents different behaviors depending on the sample preparation method, Figure 6 shows different Cyclic Shear Ratios (CSR) according to sample preparation methods, reaching values of 0.27 for WT and 0.38 for AD, both evaluated at cyclic number 20 (CSR_{20}) according to the procedure postulated by Seed (1983). As presented in Figure 1.11, Cifuentes & Verdugo (2009) and Verdugo & Santos (2009) show that sample preparation (WT and AD) had almost no effect on the undrained cyclic resistance. Figure 1.11 also shows that CSR_{20} could be as low as 0.1; under that condition, thickened tailings could be potentially liquefiable depending on the slope deposition. Scatter between different thickened tailings is considerably high, with elevated values of $CSR_{20} = 0.38$. Therefore, we cannot conclude that thickened tailings deposits are always stable under seismic events and the problem should be analyzed case by case.

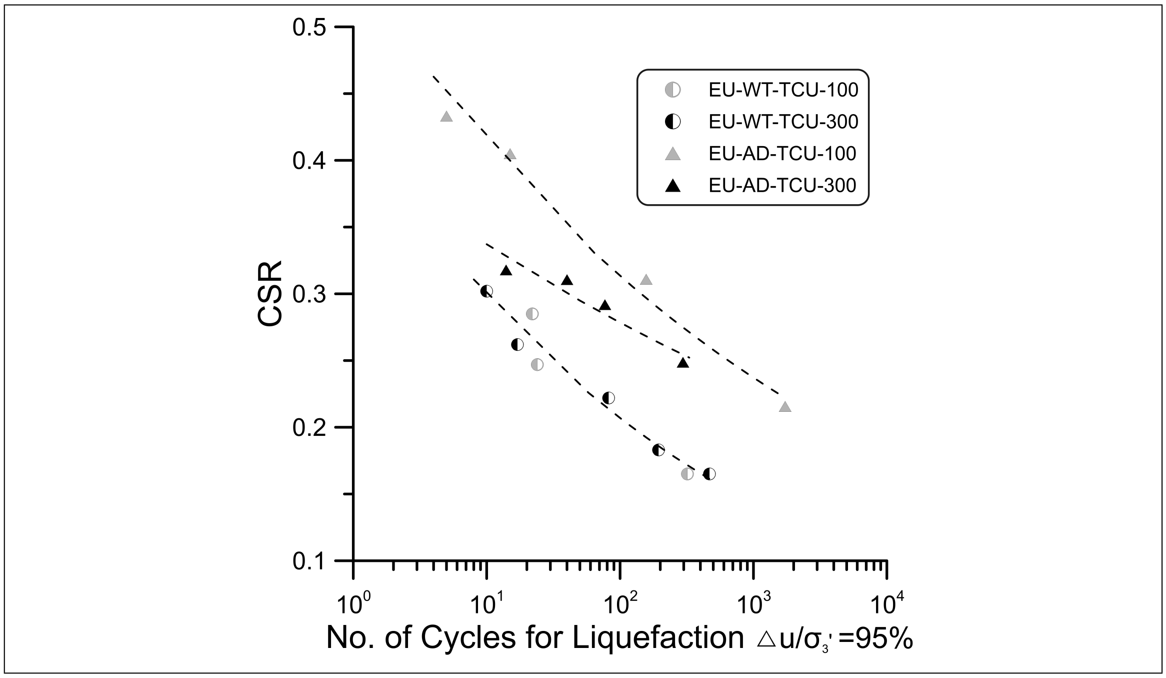

Figure 1.10. Liquefaction resistance

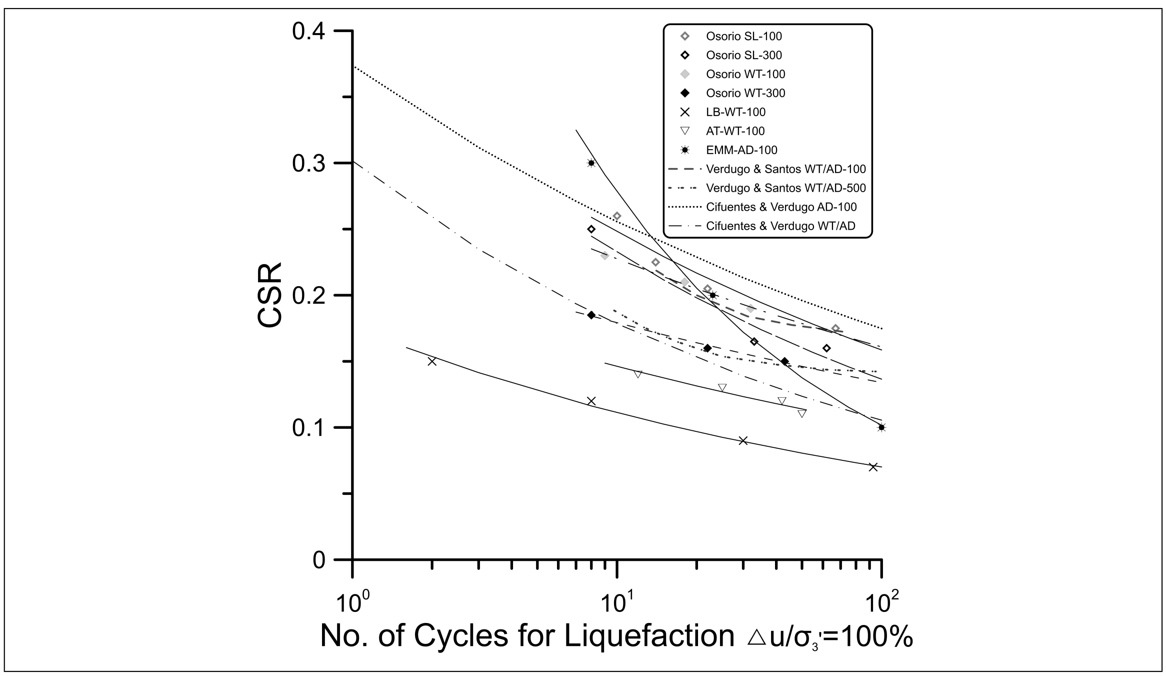

Figure 1.11. Liquefaction resistance on materials: LB, AT, EMV, and literature review

1.2.3.3. Cyclic drained response of EU materrial (shear modulus and hysteretic damping)

Figure 1.13 shows the normalized shear modulus degradation (G/Go) and damping curves of EU material. These results correspond to drained cyclic triaxial, torsional shear and resonant column tests, and the samples have different preparation methods for comparison. It can be concluded that there is no effect of sample preparation on G/Go and all cases fit closely to the curves reported for non-plastic fines by Vucetic & Dobry (1991), as well as to the lower limit recommended for sands by Seed & Idriss (1970). Figure 1.12 indicates that tests at 100 kPa of confining pressure have a slight difference on Go, but no effect of sample preparation is observed at shear strains larger than 0.003%.

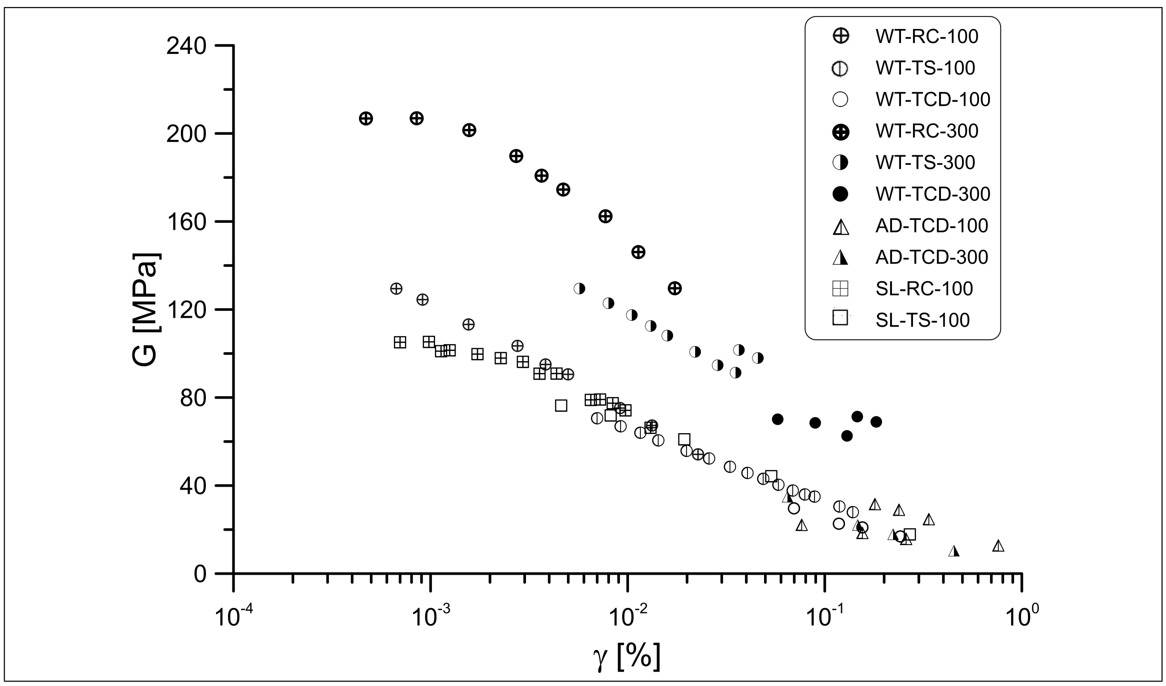

Figure 1.12. Stiffness degradation on EU material

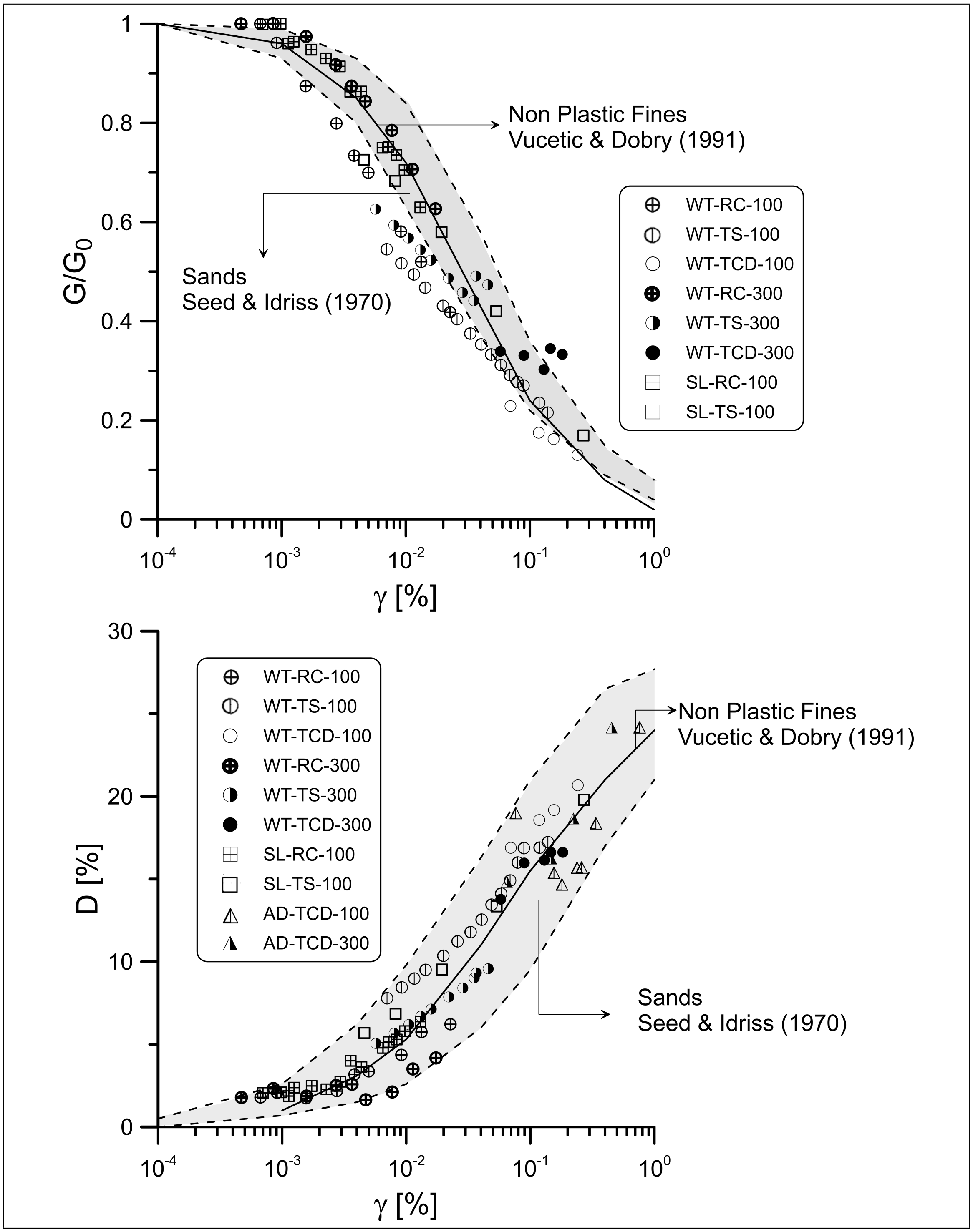

Figure 1.13. Normalized stiffness and damping cyclic degradation on EU material

1.2.4. Conclusions

The purpose of this study was to determine the effect of sample preparation on monotonic, cyclic and dynamic behavior of copper thickened tailings. With this objective, results from 5 different materials are presented, coming from 5 different thickened tailings deposits. Materials were prepared using 3 different sample methods and were subjected to monotonic and cyclic tests for an accurate characterization. Results were compared with similar materials reported in the literature. The results of this study indicate that:

- CSL and undrained strength ratio under monotonic shearing do not depend on the sample preparation method.
- Undrained cyclic behavior of EU material depends on the sample preparation method, and presents a liquefaction resistance at 20 cycle (CSR_{20}) of 0.27 for WT and 0.38 for AD. However, thickened tailings studied by other authors do not show that kind of dependency; therefore, this effect should be studied case by case.
- Results of different tailings materials show an increase of Su/σ'_3 with the fines content. This could be attributed to the drying procedure, where the densification reached by drying and shrinkage increases with the presence of fines.
- Normalized shear modulus (G/Go) and damping (D) curves for EU material present a behavior comparable to curves reported in the literature for sands and non-plastic fine soils.
- The comparison of preparation methods reveals that WT results in a Go 35% higher than SL at 100 kPa of confining pressure. Nevertheless, at shear strains greater than 0.003%, G and D are similar for the 3 different preparation methods. However, further tests under different conditions (preparation method, density, confining pressure) are required to consolidate these findings.

2. UNSATURATED FLOW CHARACTERIZATION AND MODELING OF A HEAP LEACHING COLUMN

2.1. Introduction

Leaching is a mining process used to recover copper from oxidized ores. It consists in crushing mineralized rock for generating gravel aggregates, deposit them in embankments or leach pads and irrigate them with an acid solution. This solution infiltrates and dissolves the copper, forming a solution that is collected in a baseline drainage system and carried to an extraction process by solvents and electrowinning. The outflow must be optimized to make this recovery system efficient.

This problem is related to the flow of the solution through a partially saturated porous medium. Some key parameters related to this problem are irrigation rate, gravel grain size distribution, permeability, density, and height of the structure. A better understanding of the process requires a deep material characterization and an insight in the unsaturated flow condition. Studies in this direction, together with metallurgical variables, could allow for optimization of the operation conditions for a better prediction of the ore recovery. However, few studies have been developed on this issue.

In this study, a series of laboratory tests are carried out on a grinded gravelly material collected from an operating heap leaching project, and a constitutive model for partially saturated soils is adopted to analyze this problem, implemented in the finite element code CODE_BRIGHT.

2.2. Objectives

- **General objective**

  The main goal is studying the sensitivity of the leach pad performance, varying the irrigation flow and its hydraulic parameters.

- **Specific objectives**

- Geotechnical characterization of a heap leaching material.
- Obtain the Soil Water Characteristic Curve (SWCC) in a range of densities.
- Perform tests of saturated hydraulic conductivity.
- Numerical modeling of a 1D column of a heap leaching pad.
- Sensitivity analysys of the simulation results.

2.3. Literature review

Heap leaching is a mining technique whereby low-grade ore is placed in leach pads, mostly, they have the shape of a rectangular truncated pyramid and has an irrigation system on its top. Mostly the system used is drip irrigation, then the material remained for a couple of months in the process of saturation. The aim of the system is that the acid percolates through the heap while simultaneously a chemical reaction takes place, in a process called lixiviation. At the bottom, a drainage system composed of filters and geomembranes collects the fluid and carry it to ponds, where later a process of electrowinning is carried out for separating the ore from the complete solution.

There are different building methods for leach pads, Thiel & Smith (2004) classify them in four: conventional, dump leach, valley fills, and on/off pads. The first one refers to a stack in thin layers (5 to 10 m); dump leach method is similar to the prior, but the layer has greater width (up to 50 m). Furthermore, valleys fill is a method that uses the natural field topography for being placed, and the height of the heap can reach hundreds of meters. Finally, the on/off pad system consists in depositing the material in a layer of 4 to 10 meters, leaching it and, at the end of the process, the heap is removed and disposed on another site, while the same place is used for installing a new heap and repeating the process.

It is fundamental to highlight the complexity of the problem because there are many phenomena occurring simultaneously. Therefore, in the design process contribute different disciplines, such as geotechnical engineering, mechanical, hydrometallurgy, hydrology, geochemistry, among others (Lupo, 2012; Arcos et al., 2014). The geotechnical design consists in static and dynamic stability analysis; and the study of parameters as permeability, density, grain size distribution, and shear strength foundation interface, and liner system-soil (Bard & Campaña, 2004; Guzman et al., 2008; Bennett et al., 2012).

However, there are more variables that must be considered for the leach pad design. Between these stand out the permeability in an unsaturated medium, the evolution of grain size distribution, the atmospheric conditions, the ore erosion, among others (Bard & Campaña, 2004; Lopez, 2012; Miller, 2003). Regarding the metallurgical parameters, highlight the inflow rate of acid solution and the height structure, and their relationship with the geotechnical parameters.

Permeability, grain size distribution, and density are parameters closely related; different authors have reported analysis on heap leaching materials. Lopez (2012) studied materials from three different facilities in a permeameter test, which were irrigated with water and an acid-water solution simulating the leaching process for 42 days. He concluded that the grain size distribution does not vary at the end of the leaching process for neither solution, and the density strongly affects the permeability. Also, Guzman et al. (2008) reported that both, the air conductivity and the hydraulic conductivity depend on the saturation degree of the material, and the choice of the irrigation rate is a parameter more important than the saturated hydraulic conductivity itself.

Furthermore, Yang et al. (2008) tested a column of 50 cm in height and 5 cm in diameter, with a maximum grain size of 1 cm and evaluated the evolution of permeability by a base image analysis. Results indicate that after an irrigation process of 28 days, the permeability increased in one order of magnitude, and the top zone presented a higher increase than the bottom (exclusive zone with lower permeability). Probably because of the migration of fines, also, they found that porosity decreases through the leach pad (lowest at the bottom zone).

Others factors that must be taken into account are the presence of funnel flows (preferred flows through the leach pad) and the material degradation which could be due to migration of fines or grain crushing (Thiel & Smith, 2004). Okane (2000) studied the problems derived from funnel flows and concluded that if the inflow rate is greater than the hydraulic conductivity of the fine material (k_{fine}), preferential flow occurs through the coarse material. Moreover, if the rate is lower than k_{fine}, then, the flow occurs through the fines. OKane also suggested that for choosing the irrigation rate it is necessary to know the permeability and the water retention curve of the material.

The soil-water characteristic curve (SWCC), is a function that relates suction with degree of saturation, the importance of this property in this kind of problems is that the leach pad is under unsaturated conditions throughout all the leaching process. This means that the leach pad is placed on the field at a low water content, and as time passes, it increases its saturation degree until almost achieving a saturated state at the end of the leaching process.

In the present study, numerical modeling have been developed on two kinds of models: a real leach pad facility and a permeameter, which would be a scale model for representing a column of the leach pad at small size. Tincopa (2013) used a thermo-hydro-mechanical coupled model for improving the performance of a heap leaching and concluded that a low material permeability increases the recovering time and reduces the recovered ore. Also, he has reported that high permeability produces a drop in the recovered ore. Because of that, the solution is not in contact enough time for producing the chemical reaction needed.

Cariaga et al. (2005) proposed an hydro-chemical model of a leach pad to analyze the ore recovering, they used a model whereby the initial conditions (porosity and permeability) are constant over time, however, they did not show the experimental procedures for achieving the parameters used. Moreover, Bennett et al. (2012) performed an hydro-thermo-chemical coupled model of two columns of different sizes, and different grain size distribution; the conclusion was that the change in the grading affects significantly the chemical reaction time.

The literature review revealed that few studies have focused on hydro experimental characterization and numerical simulation.

2.4. Experimental testing program

Material from a medium mining facility was collected in the field from different points of the heap; Figure 2.2 shows the collection process. This material was subjected to characterization tests as grain size distribution, hydraulic conductivity, and SWCC.

Grading tests were performed by sieving according to ASTM D 6913 with material from three different zones of the heap. Moreover, the same test was carried out on a truncated material, which was cut in $\#4$ sieve (below 4.75 mm). Furthermore, three hydraulic conductivity tests were performed according to ASTM D 5856 in a permeameter equipment at dry densities of 13.7, 15.7 and 17.7 kN/m^3, in order to represent a loose, medium and dense state. The tests were carried out in a rigid wall permeameter to constant head, using a sample of dimensions 11.8 cm in height and 10.2 cm in diameter, at the PUC geotechnical laboratory.

Figure 2.1. WP4 equipment

To study SWCC, two different methods were used for evaluating the suction at different saturation conditions. The first one was the WP4 equipment (Figure 2.1), which uses the chilled-mirror dewpoint technique and has a measurement accuracy of ± 0.1 MPa from

Figure 2.2. Material collection from heap leaching

0 to -10 MPa and $\pm$ 1% from -10 to -300 MPa. Each sample was put in a cup of measures 3.89 cm in diameter and 1.14 cm in height, the maximum volume of soil sample allowed is the half of the cup, with this restriction the volume of samples tested was around 5 cm^3. Because of the dimensions of the sample, it was not possible use the entire material, therefore, the truncated sample for this test consisted in to calibrate the equipment adequately, prepare a sample at given dry density, volume, and water content; to put the cup on the sample dish, close it and run the test.

Three hysteresis curves were carried out, this means, the samples were exposed to drying and wetting paths, each one at a different dry density of 11.8, 13.7 and 15.7 kN/m^3. In the first place, the sample was prepared at a high saturation degree, near to 80% and the test was performed. After this, with the help of heating lights for accelerating the drying process, the sample was exposed to this environment during 15 minutes. The new mass of the sample was recorded, and a new test was performed. This process continued up to reach suction values near to 300 MPa. When this value was recorded, the wetting path started. The sample was then wetted with a spray bottle in little amounts. Also, in this proceeding the new mass was recorded, the sample was put on the sample dish, and a new test was performed. Each test corresponds to a single point on a SWCC curve.

The second method used to assess the water retention curve was the vapor equilibrium technique, which is based in the relative humidity control with saturated solutions; the tests related to this and the prior technique were performed at facilities of Texas A & M geotechnical laboratory. Salts used for this propose were KNO_3, KCl, $Mg(NO_3)_2 \cdot 6H_2O$, and $MgCl_2 \cdot 6H_2O$. The salts were disposed in different desiccators, in an amount such that the solution formed with distilled water were oversaturated throughout all tests performed. Also, as the lab was an environment relatively controlled, with relativity humidity and temperature in real time imposed and controlled, this room was used as suction control too and was called Air in the results analysis.

Figure 2.3. Sample containers and desiccator

Table 2.1. Saturated hydraulic conductivity tests results

Density $[\frac{kN}{m^3}]$	Porosity [ ]	Hydraulic conductivity $[\frac{m}{s}]$
13.7	0.53	6.9E-5
15.7	0.46	6.6E-5
17.7	0.40	6.2E-5

The procedure used for this technique was the following: put in each desiccator two samples, one of them with the entire material and the other one with the truncated material at a dry density of 15.7 kN/m^3, and at a given water content. Later, the mass and temperature of each sample were measured once a week, until no variation of the mass ocurred. Then, the saturation degree was computed.

Samples were placed in plastic containers, which accounts with orifices at the bottom to ensure the transport of mass inside or outside the sample (Figure 2.3), as appropriate. Because of the long time required for a test, some of them were isolated and others samples followed a path through different desiccators, so once the same sample time was reached in one desiccator, it was moved to other and the procedure was repeated.

2.5. Experimental results

According to the United Soil Classification System (USCS), the material classifies as clayey sand for the three samples studied, as well as for the truncated sample, Figure 2.4 shows the size grain distribution for the different samples. Moreover, Table 2.1 presents results from hydraulic conductivity tests at different densities of preparation carried out on the whole material.

Figure 2.5 summarized the results of SWCC tested at 15.7 kN/m^3, performed with WP4 equipment and with the vapor equilibrium technique. Furthermore, Figure 2.6 shows the hysteretic curves carried out at different densities.

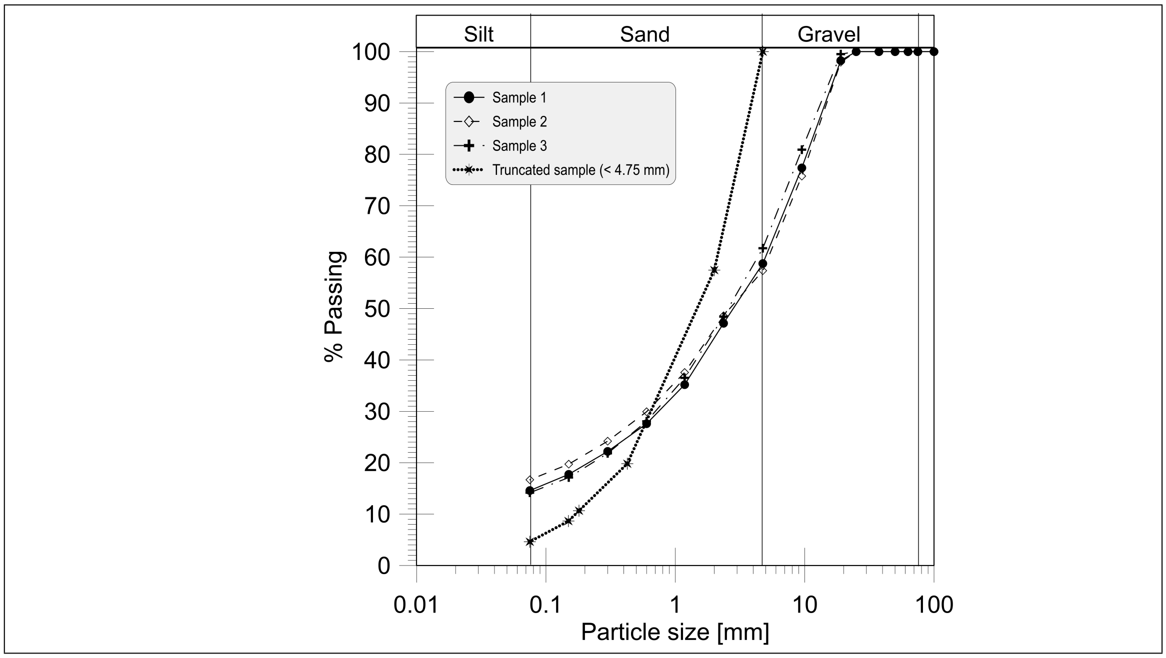

Figure 2.4. Grain size distribution

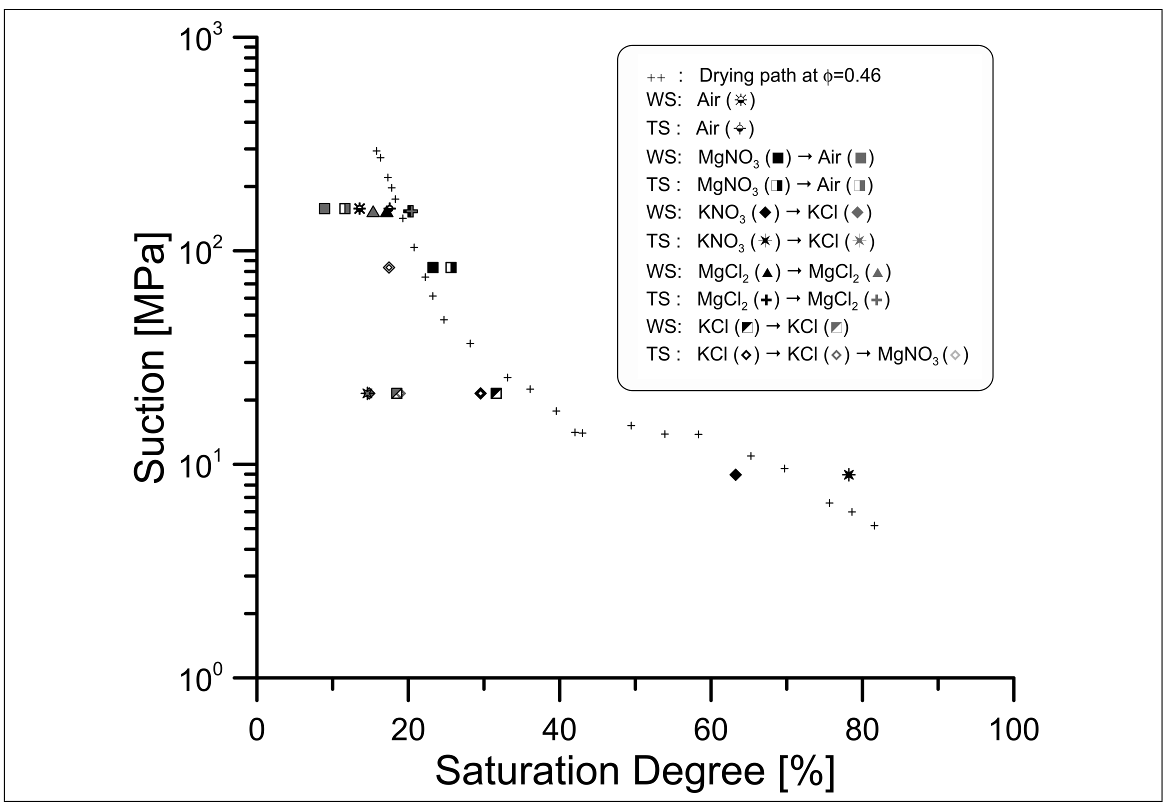

Figure 2.5. Water retention curve at preparation density of 15.7 kN/m^3

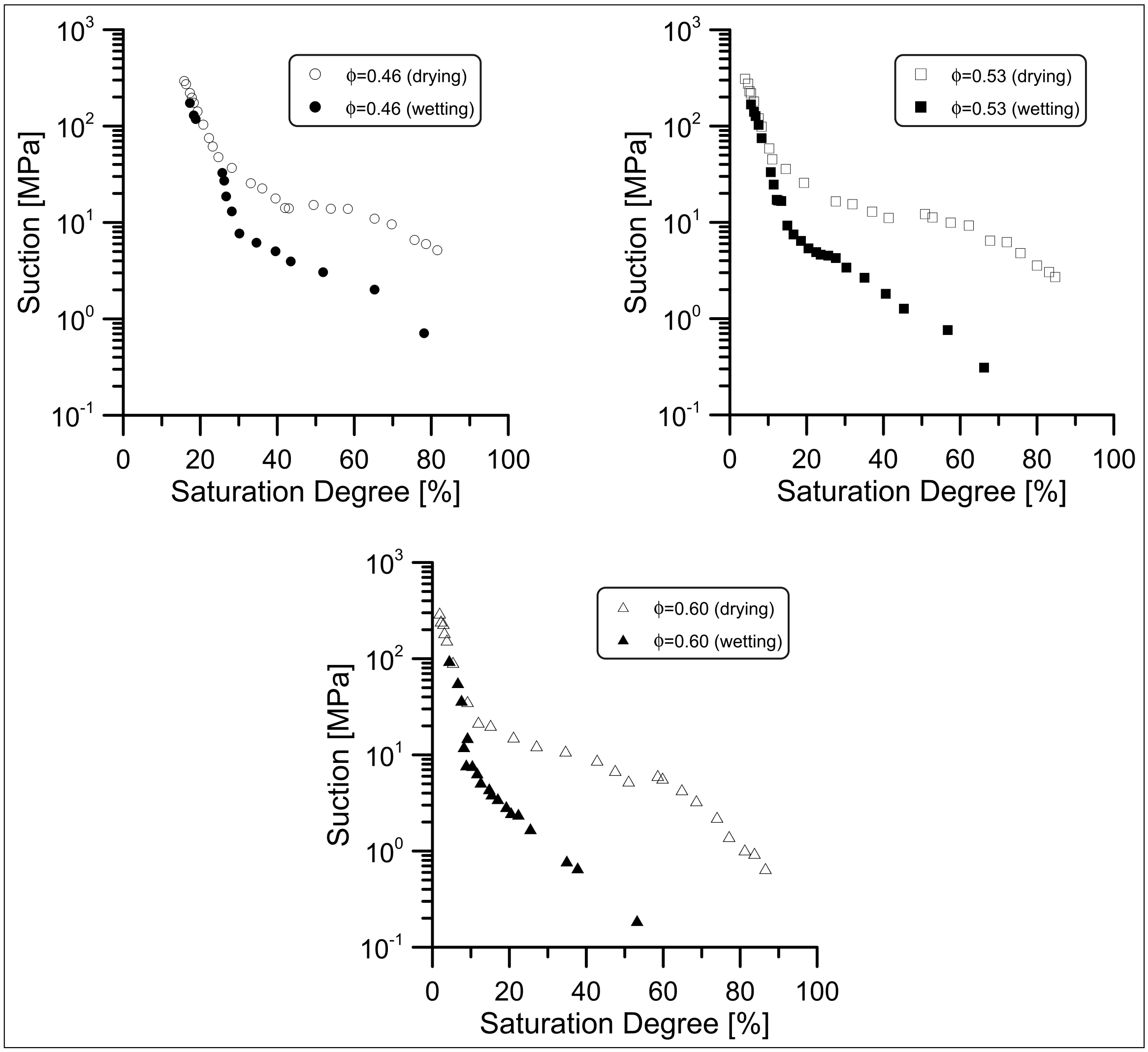

Figure 2.6. Hysteretic behavior of water retention curve at different porosities

2.6. Numerical modeling

In order to analyze the behavior of the heap during the leaching process, a numerical modeling was carried out, Section 2.10 presents the list of notation related to this analysis. For this purpose, the software CODE_BRIGHT was used, which trough the finite element method and the finite difference time-integration technique solves the balance equations by the Newton-Raphson method.

The model performed was a one-dimensional permeameter, with the aim of conducting a sensitivity analysis of the material hydraulic parameters. This study only considered the liquid phase of the problem, because of this, the equation associated was the water mass balance (Equation 2.1), which works with variables as the saturation degree, the porosity, and the liquid flow.

$$\frac{\partial}{\partial t}\left(\theta_l^w S_l \phi + \theta_g^w S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w \tag{2.1}$$

2.6.1. Calibration

Experimental results aforementioned were used for calibrating the different models. Figure 2.7 and 2.8 show the SWCC calibration for the drying and wetting respectively. The model used was the Van Genuchten curve:

$$S = \left(1 + \left(\frac{P_g - P_l}{P}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda} \tag{2.2}$$

$$P = P_o \frac{\sigma}{\sigma_o} \tag{2.3}$$

Two analyses were carried out, the first one called "A-Analysis" consisted in selecting values for Po and λ, and use them directly in the Van Genuchten model. While, the second one, "B-Analysis" took into account the porosity. For this purpose three parameters are added (a, b_1, and b_2), thus SWCC is represented by the parameters: P_o and λ; through an exponential law. Also, permeability is modeled by a similar relationship (Equation 2.6). This analysis look for capturing the effect of the porosity change in different parameters, that in fact are closely related on the field. Table 2.2 summarizes the parameters used.

$$P_o = P_o \exp(a(\phi_o - \phi)) \quad (2.4)$$

$$\lambda = \lambda \exp(b_1(\phi_o - \phi)) \quad (2.5)$$

$$k = k_o \exp(b_2(\phi - \phi_o)) \quad (2.6)$$

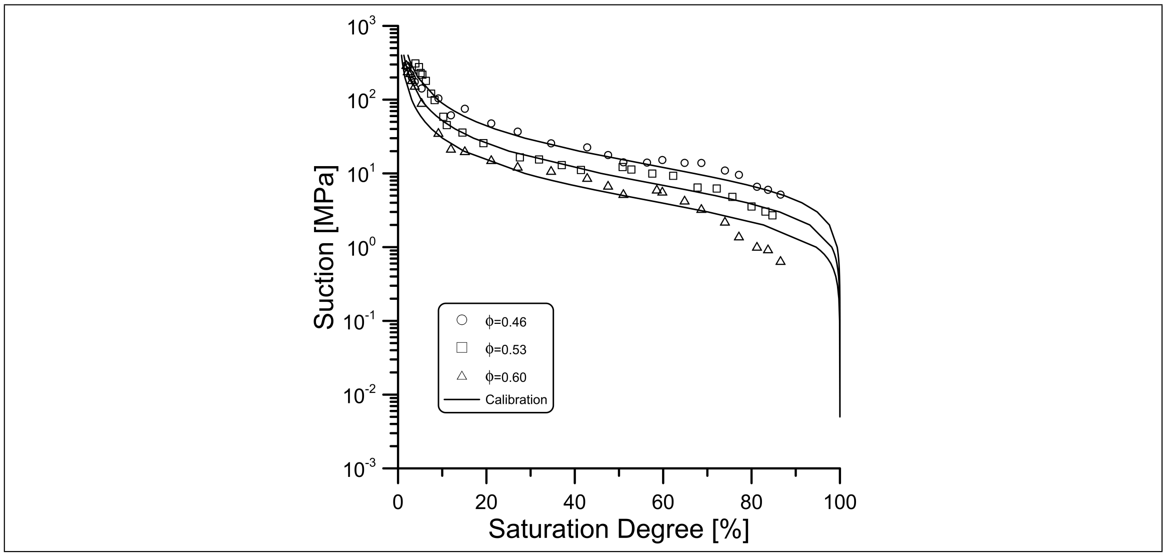

Figure 2.7. Calibration of SWCC, drying path

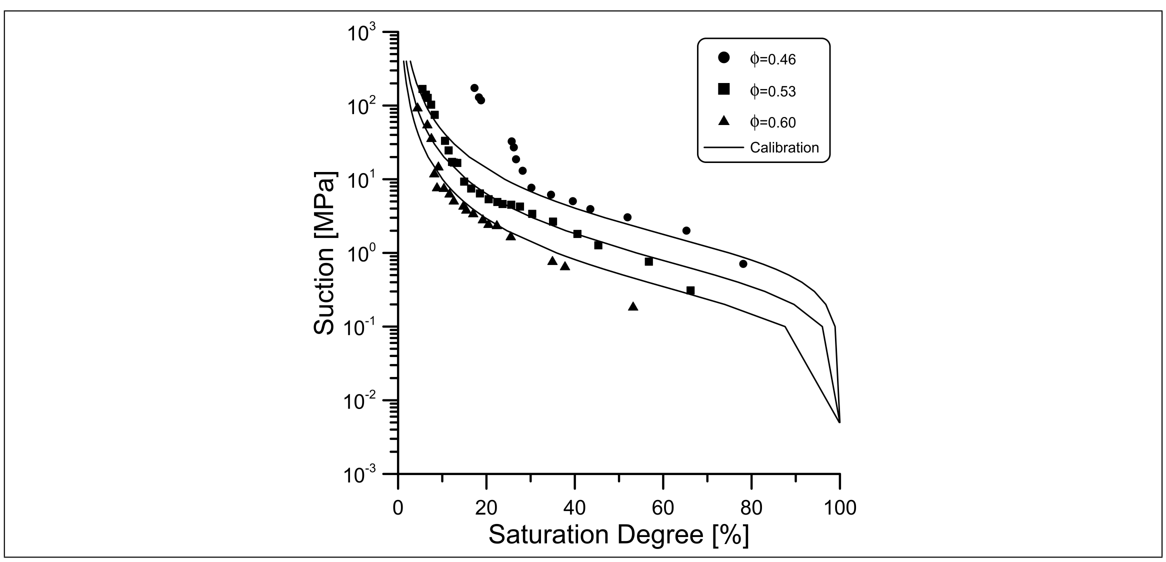

Figure 2.8. Calibration of SWCC, wetting path

Table 2.2. Parameters

Retention curve		
Parameter	Wetting	Drying
P_o $[MPa]$	0.9	9
σ_o $[Nm^{-1}]$	0.072	0.072
λ [ ]	0.37	0.5
a [ ]	12	8
b [ ]	0.2	0.05
ϕ_o [ ]	0.46	0.46
Intrinsic permeability		
$(k_{11})_o$ $[m^2]$	6.6E-12	
$(k_{22})_o$ $[m^2]$	6.6E-12	
b [ ]	0.78	
ϕ_o [ ]	0.46	
Liquid phase relative permeability		
A [ ]	1	
m [ ]	3	

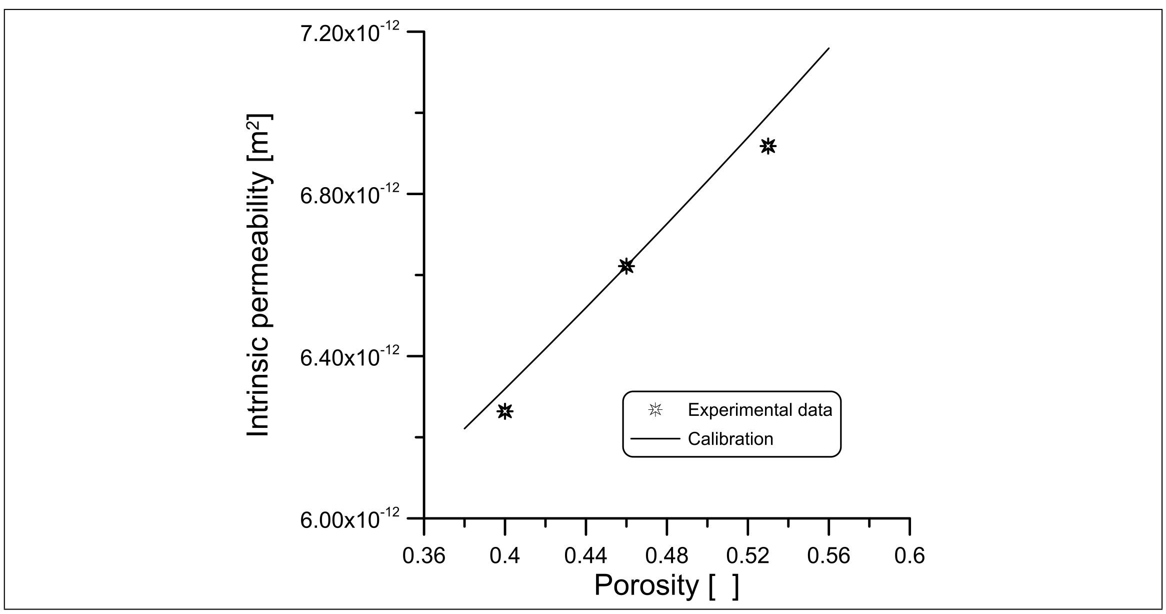

Figure 2.9. Calibration of intrinsic permeability parameter

2.6.2. Permeameter

The model intends to simulate a device similar to the one presented in Figure 2.10 (a), this is a cylindric structure with dimensions of 45 cm in height and 20 cm in diameter. At the top zone it presents a flow system, and at the bottom zone it is composed by a sand filter, in order to avoid fines migration outside the device and allow for the solution drainage. An axysimmetric model was used in the numerical simulation, Figure 2.10 (b) shows the mesh used. At the top, where a inflow is prescribed, the mesh was refined to better simulate the boundary condition. The boundary conditions at the bottom,was a prescribed flow pressure of 0.1 MPa, simulating atmospheric pressure. Finally, the right lateral condition was an impermeable boundary. On the other hand, a physical model of this permeameter is currently under construction in PUC, and will allow for the model validation in future research.

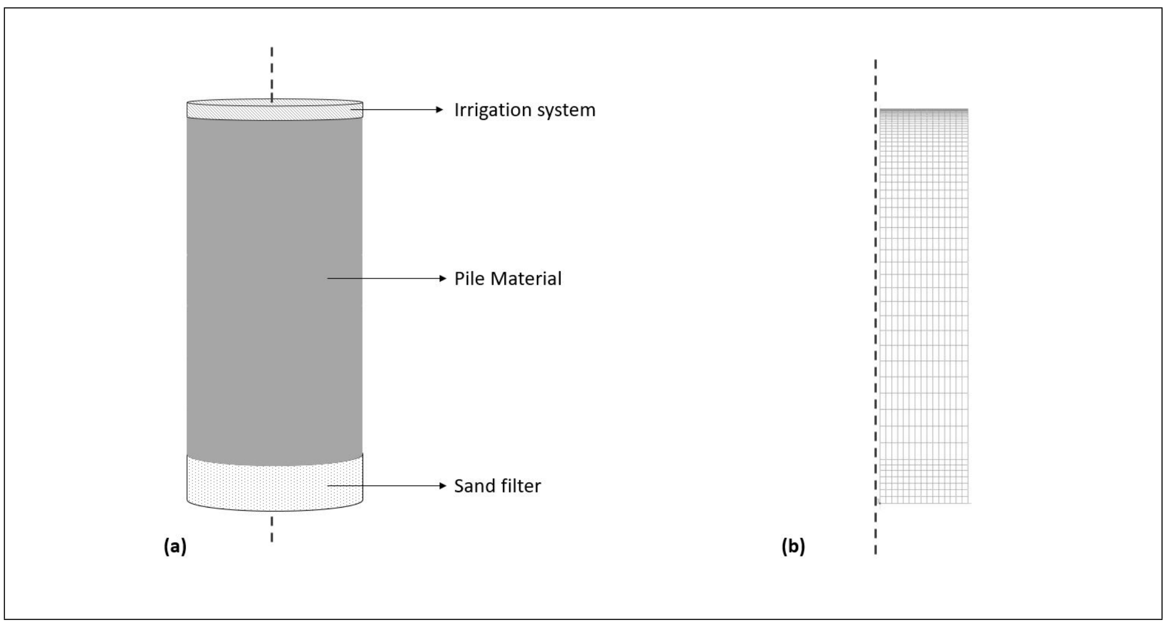

Figure 2.10. Permeameter: scheme and mesh

2.7. Numerical modeling results

A control parameter t^* was choosen in order to carry out a sensitivity analysis, defined as the time required for a point in the bottom of the permeameter to reach a steady state flow, which happens when the material in that point is fully saturated ($S = 100\%$), such as is shown in Figure 2.12. t^* is considered an important parameter for the optimization process, because the shorter the leaching time is, larger ore production in a mineral recovering facility will be. Figure 2.11 shows the A-Analysis where only one parameter was modified and all the others remain constant. It can be concluded that the change in intrinsic permeability does not affect the time of saturation, however, the variation of SWCC parameters, P_o and λ have an impact on t^*. The increase of Po produces a decrease of time, and on the contrary, the increase of λ generates a rise of t^*.

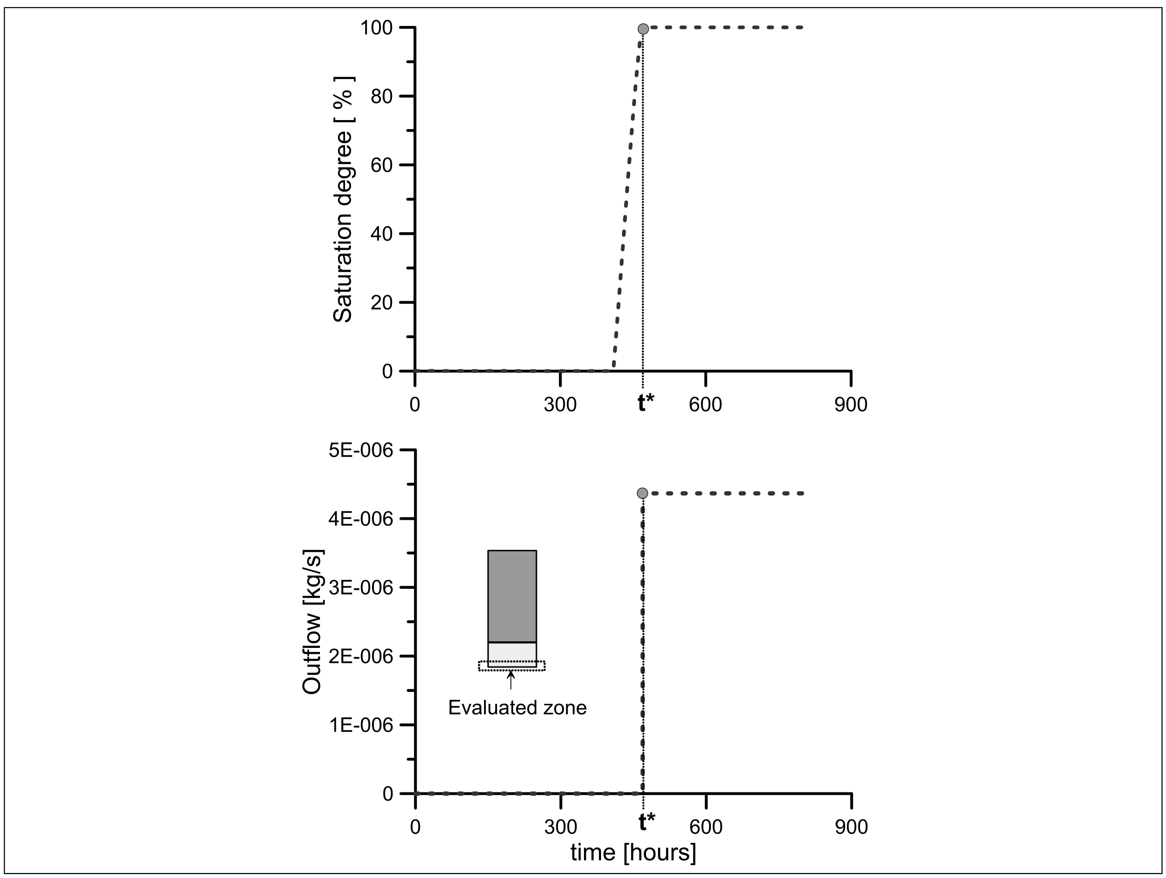

Figure 2.12. Example of saturation and outflow at permeameter bottom

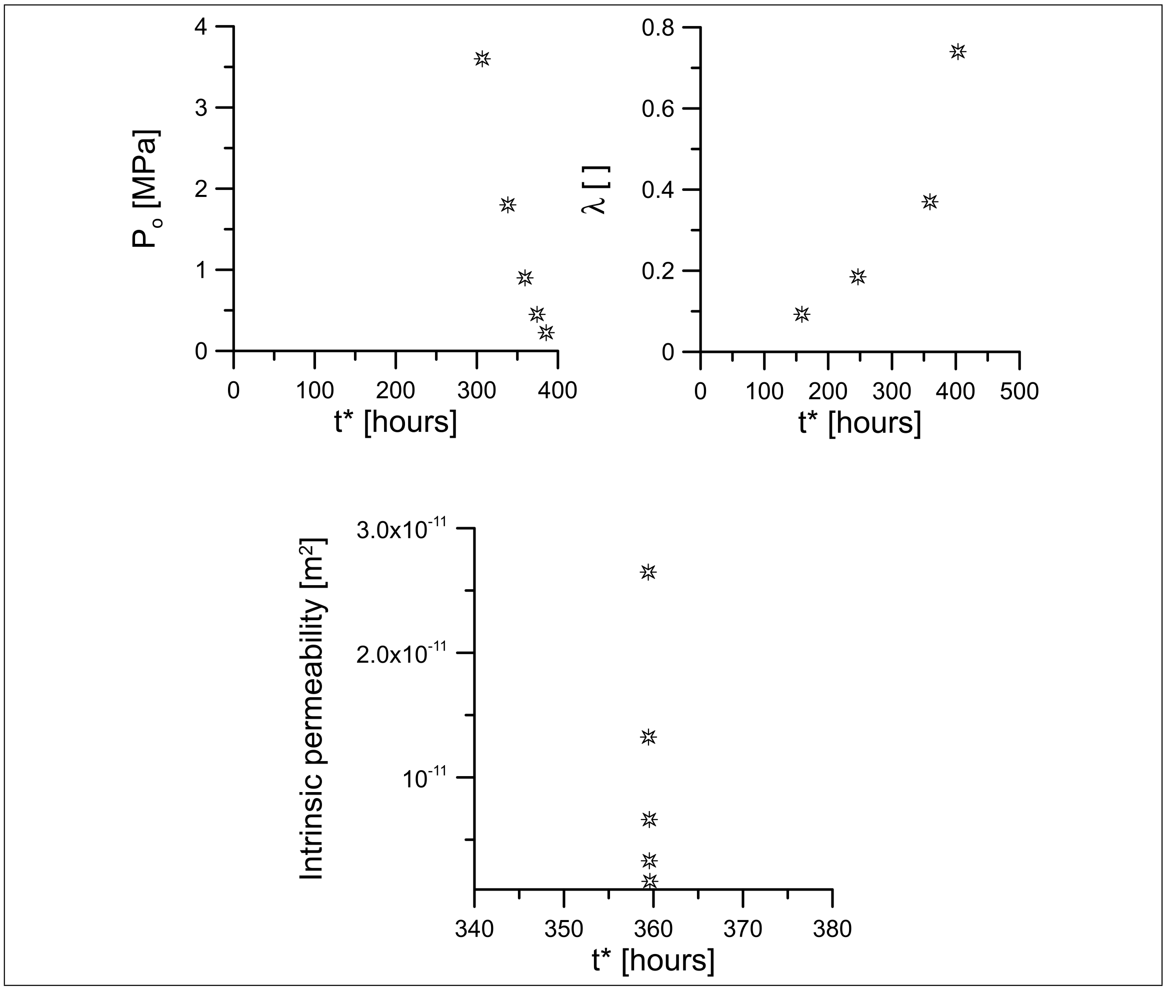

Figure 2.11. SWCC and permeability analysis

In order to analyse the influence of the hysterical SWCC on the hydraulic behavior, the irrigation flow and the porosity were studied in the numerical model. Figure 2.13 presents the results for the same prescribed flows using the SWCC parameters for wetting and drying. It can be observed that the parameters related to wetting path take a longer period of time (15% more) for reaching the saturation condition.

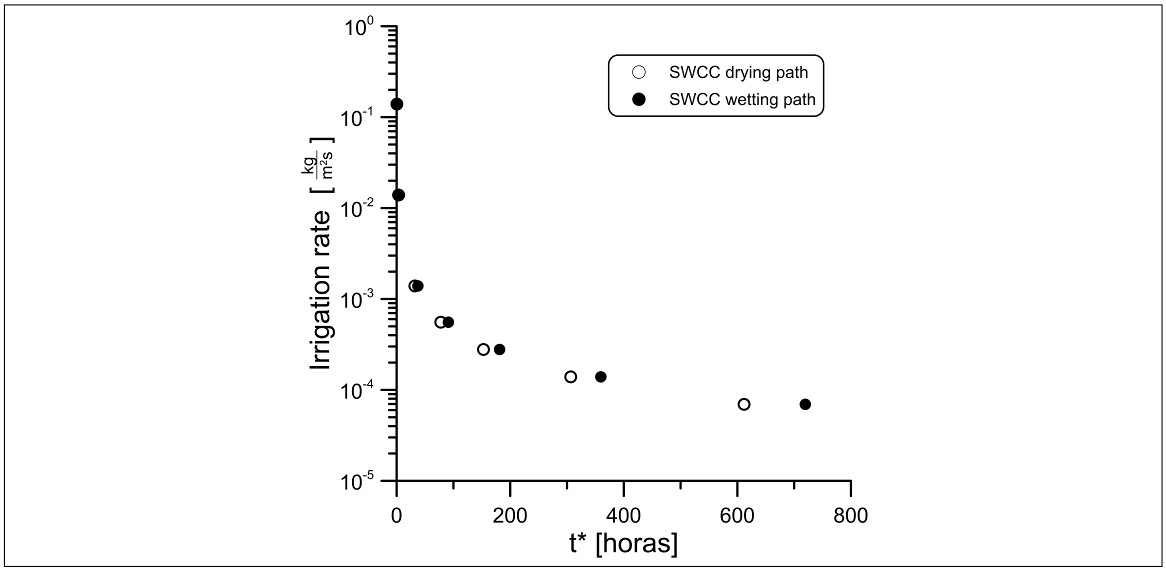

Figure 2.13. Irrigation flow analysis

Furthermore, Figure 2.14 shows that an increase in the porosity results in a rise of t^* on both analyses. B-Analysis reaches the full saturation before than the A-Analysis. Figure 2.15 presents an example of the permeameter saturation process over time.

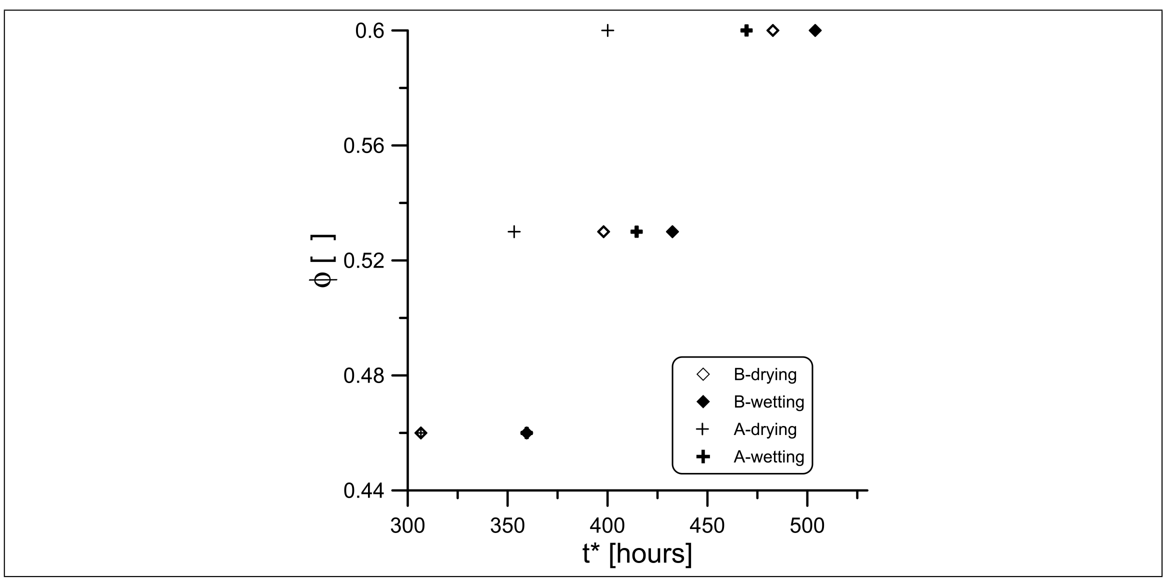

Figure 2.14. Porosity analysis with different models

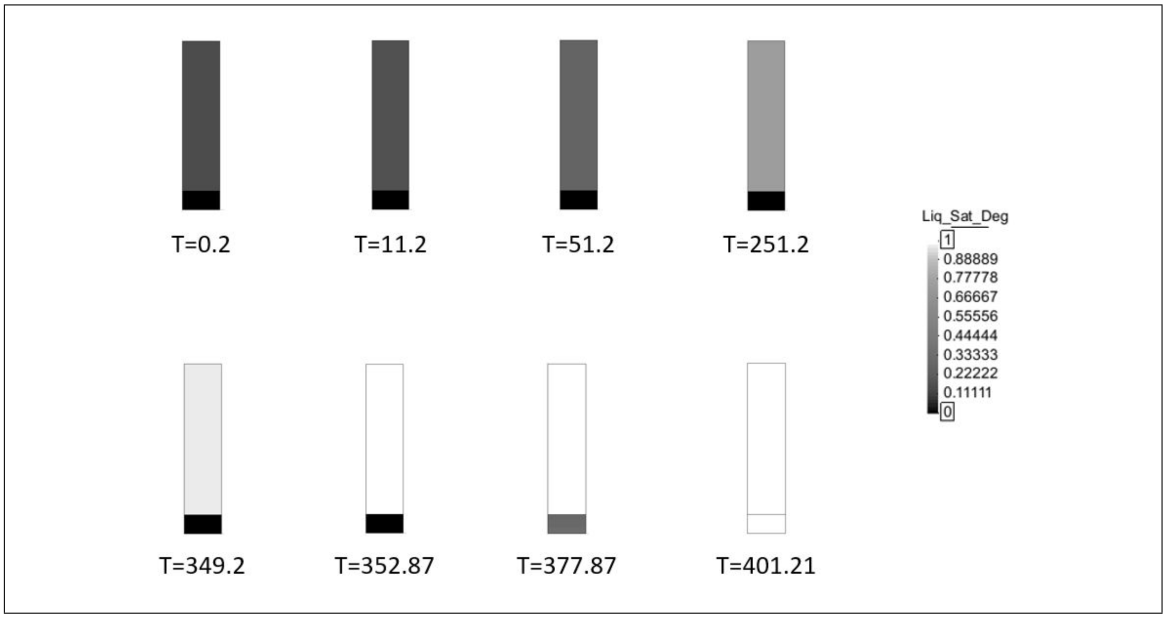

Figure 2.15. Example of saturation profile evolution with T in hours

2.8. Discussion

The experimental results of SWCC from WP4 showed an hysteresis loop well defined. When compared with the results from vapour equilibrium technique, most of samples present a good fit as shown in Figure 2.5. Also, the same figure shows that the average difference in saturation degree for the whole and the truncated sample is only 4.3 %. Therefore, the truncated sample could be reasonably considered as representative of the whole sample, when it is studied a grain size distribution greater than the allowed for testing equipments.

The sensitivity analysis presented from numerical modelling shows that the key parameters to be taken in account are the inflow rate and the SWCC. Specially, the effect produced by the water retention path is relevant, wetting path needs more time for saturating than drying. This fact is relevant because several reported studies do not specify how the SWCC was obtained, consequently if the curve used was the drying one, the results would be underestimated in terms of time.

Moreover, the simple analysis of the permeability parameter shown it as an independent parameter for the values considered. This result is similar to the reported by Guzman et al. (2008), and can due to that the effect of the permeability change is not produce by the value itself, otherwise, for the effect that it generates in the SWCC, that is the key parameter.

2.9. Conclusions

The purposes of the current study were to characterize the material, obtain the soil water retention characteristic curve and develop a sensitivity analysis of the hydraulic behavior in a heap leaching facility. With this aim, the material was characterized by WP4 and vapor equilibrium technique, in order to get the SWCC and, also grain size distribution and saturated permeability tests were performed. Later, a sensitivity analysis was performed simulating the material on a permeameter test. The results of this study indicate that:

- The material soil water characteristic curve presents a hysteresis loop well-defined and it is a critical parameter on the model sensitivity. The drying curve allows a saturation faster than the wetting curve.
- The vapor equilibrium technique exhibit a good fit compared to data obtained from chilled mirror dew point technique.
- A change in the material permeability does not affect the saturation time; it seems not be influential for the range of values whereby it is found the material studied, which is rather limited.
- The SWCC parameters λ and P_o presents influence in the saturation process, as well as the porosity of the material.

Moreover, further work is needed to confirm and validate these findings. Future research could be to carry out a permeameter and perform several tests measuring variables as suction, temperature, mass, and humidity. In order to feed the model and adjust in a better way the parameters. Finally, it would be interesting to analyze a real heap leaching structure with a more complex model, for example, a thermo-hydro-mechanical model.

2.10. List of notation

ϕ : is the porosity of the material

θ_p^w : is the mass content of water in the phase p, with p: liquid, gas

S_p : is the degree of saturation related at the phase p

$\mathbf{j}_l^w$: is the total mass flow of water in the liquid phase

f^w : is the external supply of water

P_g : is the gas phase pressure

P_l : is the liquid phase pressure

λ : is the shape function for retention curve

P_o : is a measured of pressure at a temperature T

σ : is the surface tension

σ_o : is the surface tension at the same temperature that was measured P_o

a : is a parameter for coupled the porosity influence on the SWCC

b_1 : is a parameter for coupled the porosity influence on the SWCC

ϕ_o : is the porosity of reference

k_{ii} : is the intrinsic permeability on the direction ii

k_o : is the intrinsic permeability of reference

b_2 : is a parameter for coupled the porosity influence on the permeability

A : is a constant of the generalized power model for evaluate the liquid phase relative permeability

m : is the power of the liquid phase relative permeability function

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