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# Physical models consolidation by electro-osmosis

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## ABSTRACT

This paper shows in details results from a comprehensive experimental program that has been carried out in the Centrifuge Laboratory of UENF, where many geotechnical problems have been assessed with physical models. In particular, this study was related to consolidation of physical models of clayey mud using electro-osmosis. Two sets of electrodes were used, the first one to promote radial flow while the second one, one dimensional flow (vertical). The results of these early studies, where a profile of geotechnical parameters like undrained shear strength ( $S_u$ ), water content, and specific weight, obtained before and after electro-osmosis consolidation, are presented here. These tests were performed in an electro-osmosis cell developed to be used to model the seabed of Campos Basis (BRAZIL/RJ). The results show that the electro-osmosis is suitable to consolidate clayey mud in laboratory.

## RESUMEN

En este trabajo, se muestran en detalles los resultados de un amplio programa experimental que se ha llevado a cabo en el Laboratorio de Centrifuga de UENF, donde muchos de los problemas geotécnicos se han evaluado utilizando modelos físicos. En particular, se ha demostrado la consolidación de modelos físicos de barro arcilloso a través de electro-ósmosis. Dos juegos de electrodos se utilizaron, el primero para promover el flujo radial, mientras que el segundo, flujo unidimensional (vertical). Los resultados de estos primeros estudios, un perfil de los parámetros geotécnicos como la resistencia al corte sin drenaje, contenido de agua, y la gravedad específica obtenidos antes y después de la consolidación de electro-ósmosis, se presentan en este documento, además de una célula de electro-ósmosis desarrollada para ser utilizada para modelar el lecho marino de Base de Campos (Brasil / RJ). Los resultados muestran que la electro-ósmosis es adecuada para consolidar el barro arcilloso en el laboratorio.

## 1 INTRODUCTION

Physical modeling in miniature scales requires a similitude and similarity studies that are well known by research groups that work with modeling in geotechnical centrifuge. Moreover, researchers have to use many procedures that are uncommonly used like uncommon materials and procedures. Mixing of powder materials and soil of different plasticity index, consolidation technique, miniatures instrumentations, non usual fluid to simulate the water under increased gravity are examples of them.

Electro-osmosis technique is used in Civil Engineering in order to promote water seepage, consolidation and increase of the load capacity of clayey soils, to accelerate the soil settlements, and also to remove the pollutants from sub-soils. All these points were proved in the engineering practice, although, actually, this technique is not commonly seen in the practice of engineering field, maybe because of the costs involved when it is compared to other technologies.

In the past of UENF Civil Engineering Laboratory, a research to assess the performance of electro-osmosis in remediation of contaminated sites was carried out. In this work, the electro-osmosis cell was developed and tested. The results show that the electro-osmosis is suitable to promote transportation of pollutant in contaminated soil (Laurindo, 1999). Mitchell (1993) showed in details the

electro-osmosis application in laboratory studies and presented all aspects of the electro-osmosis technique.

In a recent research, in the Centrifuge Laboratory of UENF, electro-osmosis has been applied in order to consolidate clayey mud. The earliest findings of this research are presented here.

## 2 ELECTRO-OSMOSIS THEORY

Electro-osmosis is one of the electro-kinetic phenomena that occurs when an electric potential is applied across a wet soil mass. Cations are attracted to the cathode (negative) while anions are to the anode (positive). The water is dragged both by cations, causing a water flow to the cathode, and by anions, resulting a water flow to the anode. The flow into anode direction is much smaller than the flow into cathode direction. Therefore, the electro-osmosis results in a higher hydraulic gradient to the cathode (Figure 1). Mitchell (1993) states that if in compressible soil electro-osmosis draws water to a cathode, where it is removed from the system, and no water is permitted to enter at the anode, consolidation of the soil between the electrodes occurs in an amount equal to the volume of water removed. Thus, if a consolidation is supposed to occur around the anode, because the pore pressure decreases while the total

stress remains unchanged, the undrained shear strength must increase while the dry gravity of soil and water content in the vicinity of the anode decrease. Electro-osmosis depends on different components of the system as well as soil type, water content, pH and electrolytic concentration.

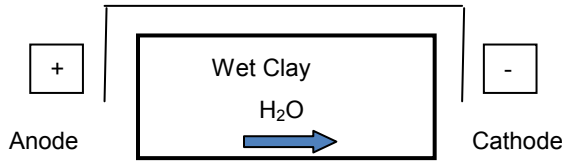


Figure 1. Graphical representation of the process of electro-osmosis

The efficiency of electro-osmosis in consolidation of cohesion soils was proved by field investigation carried out by Casagrande (1949) e Bjerrum et.al. (1967) - apud Mitchell (1993). Furthermore, electro-osmosis was applied associated with vertical drains by Shang (1998) in a consolidation project of a natural clay deposit.

The widely known and used mathematics model is the Helmholtz-Smoluchowski Theory (Smoluchowski, 1921). This model takes in account that the osmotic flow happens due to the interaction of diffused double layer at the soil-fluid interface and fluid in the pore. In Figure 2, it is shown a schematic diagram of this theory. Steps 1, 2, 3 and 4 show different stages of water flow until the electrical field is completely set up.

Helmholtz-Smoluchowski described electro-osmotic flow with Equation 1

$$q_{eo} = -A \frac{-\varepsilon \tau}{\mu} n \nabla \phi \quad [1]$$

where: A is the area perpendicular to flow direction;  $\varepsilon$  is the fluid permittivity;  $\zeta$  is the Zeta potential;  $\mu$  is the fluid viscosity; n is the medium porosity;  $\phi$  is the voltage.

$$q_e = k_h i_h + k_e i_e \quad [2]$$

where:  $k_h$  is the hydraulic coefficient of permeability,  $k_e$  is the electro-osmotic coefficient;  $i_h$  and  $i_e$  are the hydraulic and electro-osmotic gradient, respectively.

The electro-osmotic conductive coefficient parameter ( $k_e$ ) is independent of pore size but strongly dependent on soil mineralogy and mainly on superficial charge and zeta potential.

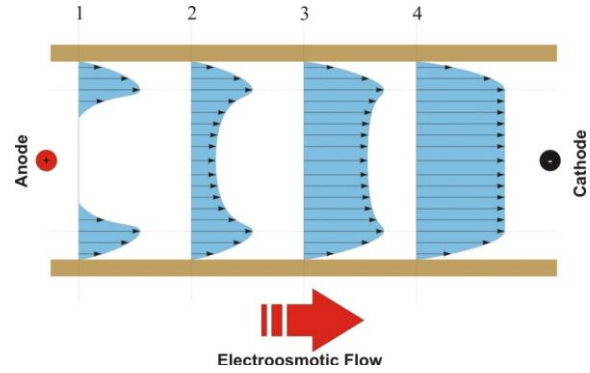


Figure 2 - Schematic of electro-osmotic flow in the soil particles (Grosso et al, 2007)

### 3 MATERIALS AND METHODS

#### 3.1 Electro-osmosis Cell

An electro-osmosis Perspex acrylic cell was projected in order to assess consolidation of a considerable volume of soil by its technique. The Perspex wall has a 338mm inner diameter and 500mm height. The base of this cell has an appropriate place, at the center of it, to install a total stress transducer that was not used in this study, and a drained box. In the base, four drain holes were perforated to drain fluid, fill cell with water and measure the pore water pressure. A double cell top was projected to allow a hydraulic consolidation test accomplish. Both the base and the cell top can be observed in Figure 3.

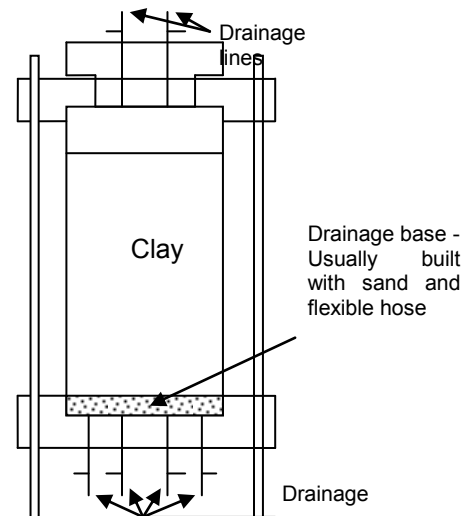


Figure 3. Container used in this research program

As we can see in the following topics, two sets of electrodes were used. The first one, the electro-osmosis was applied to promote radial flow while the second one, a vertical (one-dimensional) flow was established.

### 3.2 Description of soil samples

The materials used to compose the mixture of the mud were meta-kaolinite and kaolin. Geotechnical characterization testing, concerning about grains size distribution curve, Atterberg limits and oedometer consolidation tests of different content with these materials, were performed, and one mixture was chosen. Thus, the mixture chosen was composed by 60% of meta-kaolinite plus 40% of kaolin. The results of geotechnical characterization tests of this mixture are presented in Table 1. In Figure 4, the grain size distribution curves are shown.

Table 1. Parameters of geotechnical characterization

Material	Grain size distribution			G	Atterberg limits	
	Clay	Silt	Sand		LL	LP
Meta-kaolin	19,3	74,9	5,8	2,60	NP	NP
Kaolin	45,7	53,5	0,8	2,66	68,9	34,3
Mixture	25,4	58,8	15,7	2,64	62,5	35,7

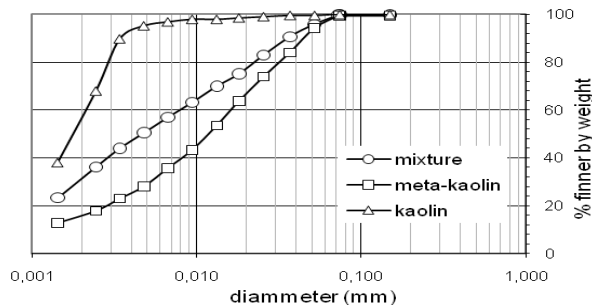


Figure 4. Grain size distribution curve

The materials, 13.5 kg of meta-kaolinite plus 9 kg de kaolin, were placed in the colloidal mixer with approximately 28.1kg of distilled and de-aired water. The water volume corresponds to 2 times the limit liquid of the mixture. The mixer was kept working during approximately one hour in order to obtain a homogeneous mud. It was transported to a concrete mixer adapted with vacuum supply, so as to guarantee a de-aired mud. It was kept working also during approximately one hour. Then, the mud was taken from the mixer, placed carefully in the electro-osmosis cell, and kept resting during 48 hours. Sedimentation and consolidation process by own weight during this time were observed.

### 3.3 Radial set to electro-osmosis consolidation

In the radial set, the anodes, four metallic solid rod of 5 mm diameter, were placed with equal distance, closed to 13.3 cm, to the center of the cell where the cathode was installed. The cathode was 10 mm diameter metallic tube

(Figure 5). This tube was totally perforated in order to drain water easily. A 25 DC voltage was applied during approximately 5 hours. The test was stopped due to the occurrence of many shrinkages at the top of the sample. The settlement was measured by a ruler placed in front of the cell.

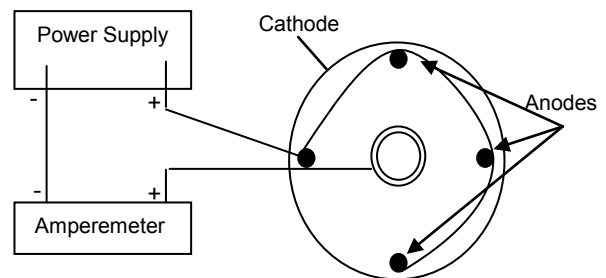


Figure 5. Radial electro-osmosis schematic and apparatus

### 3.4 Vertical set to electro-osmosis consolidation

In the vertical set, the electrodes were two drilled cooper plates to allow drainage; one was placed at the top of the mud and the other on the drainage layer. In order to prevent the formation of shrinkages at the top of the sample, it was used an overload. In Figure 6, it is shown a picture and a schematic of a cell to promote a vertical flow.

After the sedimentation and consolidation process by own weight, there was an added overload at the top before starting the process of electro-osmosis. The current was applied in steps as described in the Table 2. In the last step, the electrical field was inverted; the aim of the inversion was to obtain a homogeneous clayey mud. The displacement of the sample top was measured continuously during all testing-time. Those steps were developed after the execution of various tests. Mini vane shear test was performed before the polarity reversal and after it to measure the increase of undrained shear strength ( $S_u$ ).

In Figure 6, schematic drawing of vertical electro-osmosis settling is shown, with power supply [1], amperemeter [A] and electrodes [2]. The directions of

water flow in the soil column are presented in the Figure for the two stages applied in this work.

Table 2. Steps of electro-osmosis vertical

Steps	Duration (h)
Consolidation own weight	60
Placement overload (5kg)	16
Electro-osmosis 10VDC (positive bottom) + overload 10kg	06
Electro-osmosis 20VDC + overload 10kg	03
Electro-osmosis 20VDC + overload 20kg	24
Overload 20 kg	18
Electro-osmosis 25VDC + overload 20kg	02
Electro-osmosis 30VDC + overload 20kg	05
Overload 20 kg	17
Inversion electro-osmosis 20VDC + overload 20kg	24
Inversion electro-osmosis 25VDC + overload 20kg	04

### 3.5 Laboratory mini vane shear test

The undrained shear strength ( $S_u$ ) was assessed by a laboratory vane test. This device is a 12.7 mm height and 12.7 mm diameter. It is introduced into the mass of soil at a rate of 0,1mm/s until the depths redefines pre-defines where the  $S_u$  was measured. After 60 seconds at a desired position, the vane is turned on at a rate of 1°/s until it reaches 180° clockwise. During the tests, torque forces are measured with a Wheatstone bridge placed close to the vane. This configuration was carefully calibrated to have the  $S_u$  calculated (see Eq. 3).

$$S_u = \frac{T}{\pi \cdot d^2 \left( \frac{h}{2} + \frac{d}{6} \right)} \cdot 9,81 \times 10^{-8} \text{ kPa} \quad [3]$$

where: T (kNm) is the torque forces measured; d (m) is the vane diameter; and h (m) is the vane height.

## 4 RESULTS

In the early vane test, where the consolidation was done only by its own weight, a profile of undrained shear strength ( $S_u$ ) was defined. It shows that even after this step, the  $S_u$  was very low, reaching values from 1,54 kPa

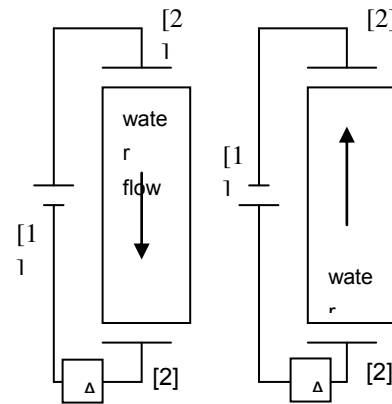
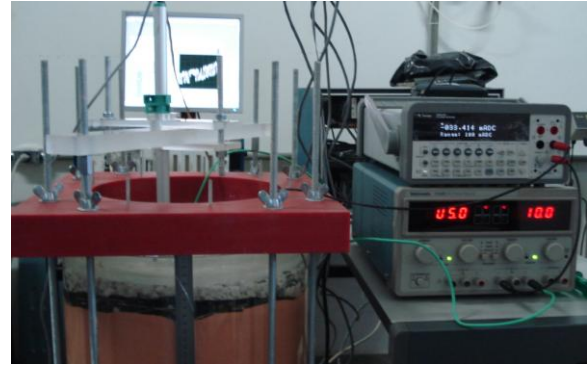


Figure 6. Electro-osmosis apparatus: [1] Power supply, [2] Electrodes, [A] Amperemeter

to 2,44 kPa. Both tests did not show any tendency with depth.

Because of the low shear strength profile, the sample was consolidated using radial set of electro-osmosis. The peak values obtained for  $S_u$  were from 3,73 kPa to 42,43 kPa, as presented in the profile of Figure 7. As a disadvantage of radial electro-osmosis, deep shrinkages were observed in the sample surfaces (Figure 8), so this case was discarded.

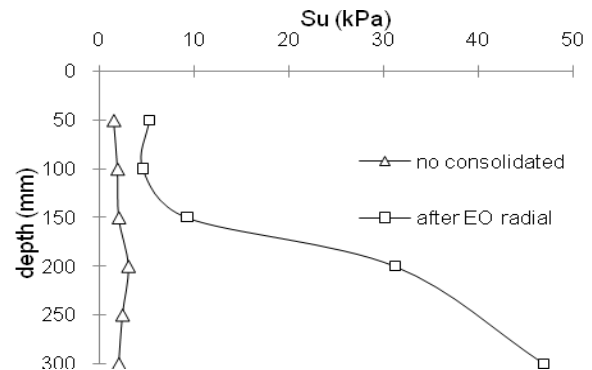


Figure 7. Profiles of undrained shear strength before and after process of consolidation by radial electro-osmosis

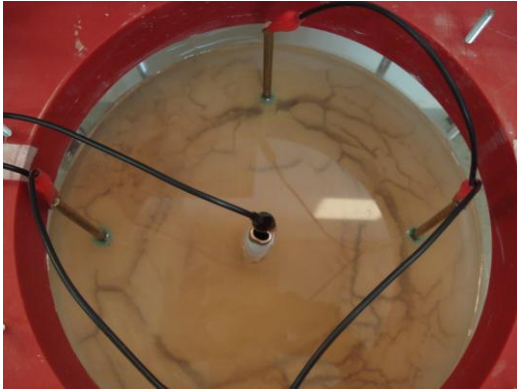


Figure 8. Shrinkages on the surface of the model after the radial electro-osmosis

Thus, a vertical set to electro-osmosis consolidation was applied using other types of electrodes, placed at the top of the sample and at the bottom (Figure 6) with the addition of the overload. This set promotes a vertical flow, initially, from the bottom to the top, resulting in an increase of  $S_u$  at the bottom of the sample, with values of 3.66 kPa to 25.19 kPa. In order to improve the  $S_u$  in the upper layers of the sample, the polarity was changed, inverting the flow gradient. The values at the top of the sample become larger, after reversing, approximately 17 kPa, and lower layers, close to 16 kPa. These results are in accordance with electro-osmosis theory where the anode vicinity becomes more resistance than the cathode vicinity. The resistance decreasing at the sample bottom suggests a change in soil structure. This change is caused by the inversion of polarity that channelizes the flow of water toward the base of the sample. Besides this, the occurrence of shrinkages in this region also may influence the difference in resistance value, as shown in Figure 9.



Figure 9. Shrinkage at the bottom of model after reversal of polarity

Then, undrained shear strengths were determined with a mini vane test. The profiles of  $S_u$ , after each process, are showed in Figure 10. In Table 3, all

undrained shear strength calculated with mini vane test are presented.

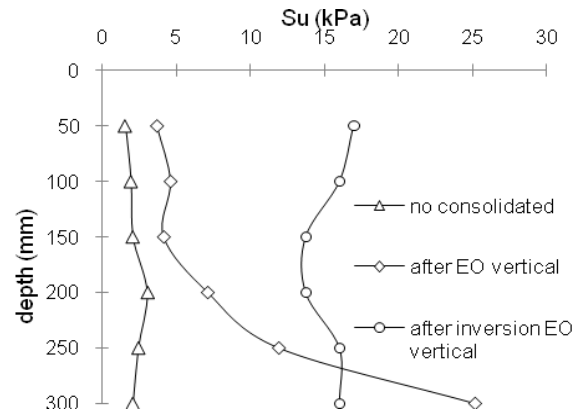


Figure 10. Profiles of undrained shear strength before and after each process of consolidation by electro-osmosis.

The results of settlement measured during the stages of consolidation are shown in Figure 11.

Table 3. Steps of electro-osmosis vertical

Depth (mm)	Undrained Shear Strength (kPa)			
	No consolidated	After EO radial	After EO Vertical	After inversion EO Vertical
50	1.54	3.73	3.66	16.98
100	1.93	4.63	4.58	16.03
150	2.06	6.37	4.12	13.74
200	3.06	8.10	7.10	13.25
250	2.44	26.74	11.91	16.03
300	2.06	42.43	25.19	15.94

After the tests, a sampling spoon was inserted to obtain a profile of undisturbed sample to evaluate some soil index as water content, void ratio, degree of saturation and dry unit weight. The water content vs. depth is presented in Figure 12. It was observed that the water content at the bottom and at the top of the sample is smaller than in the middle of the sample. This occurs due to the release of water in the region of the anodes.

## 5 CONCLUSIONS

The results presented in this paper suggest that the electro-osmosis is suitable to consolidate physical models of mud clay. It is easily proved by comparing the undrained shear strength measured before and after the electro-osmosis consolidation.

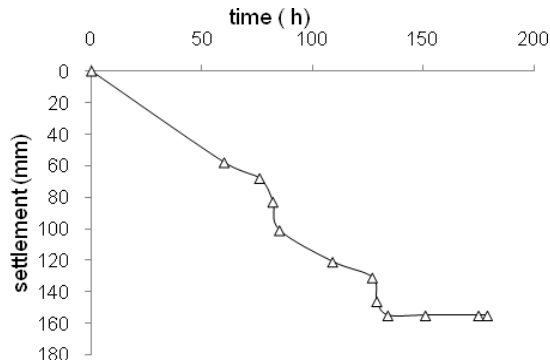


Figure 11. Settlement measured during vertical set electro-osmosis consolidation

The result of undrained shear strength after radial set to electro-osmosis consolidation reaches value close to 42.0 kPa at 300 mm depth from the top of the soil. The results, after inversion of the polarity in the vertical process, reach values close to the 16 kPa, independently of the depth.

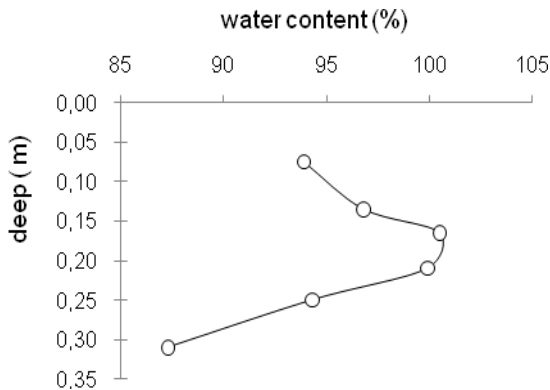


Figure 12. Profiles of water content after process of consolidation by vertical electro-osmosis

Based on this study, it can be noticed several peculiarities in the process of consolidation by electro-osmosis. The first one is the influence of the integrity of the electrode, because of the oxidation that occurs during the process of electro-osmosis. The second one is the need of overload in order to avoid shrinkages at the top of the sample. The formation of bubbles in the mass of soil close to electrode, indicating the occurrence of electrolysis with production of hydrogen gas in the cathode region, is the last peculiarity.

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