Electro-osmotic consolidation of soft tropical clay in laboratory trial

Nascimento, A.J.P. & Murrieta, P.S.N.
Department of Civil and Environmental Engineering, University of Brasilia, Brasilia, DF, Brazil

Keywords: electro-osmosis, consolidation, electro-conductive drain, tropical soil

ABSTRACT: Electro-osmotic consolidation using electric conductive geosynthetics has been studied in some research centers in Asia and Europe. In this paper, laboratory tests were carried out using electro-conductive and non-electroconductive drains incorporating geotextile filters in an electro-osmotic cell on reconstituted soft tropical clays. The main objective of this study was the improvement of electro-osmotic parameters to accelerate consolidation of fine grained soils using large-scale tests. Therefore, the investigation was conducted with different concentrations of salt (0g/L, 16.5g/L and 33g/L), under different effective stresses (50kPa and 100kPa) and different voltage gradients (25V/m, 75V/m and 125V/m). The comparative influence of these factors on the current variation, settlement, undrained shear strength, water content and energy consumption is important for this study. Thus, in terms of cost-benefit, the electro-osmotic consolidation test under 25V/m voltage gradient, 50kPa surcharge load with salt concentration of 16.5g/L salt presented the best performance. The settlement attained using electro-osmotic consolidation was 65% greater than that for the sample without electro-osmotic consolidation. Besides, the shear strength was 170% greater than that achieved using conventional consolidation treatments. However, this study recognizes important factors that may influence the efficiency of electro-osmotic consolidation and have also investigated problems associated with corrosion of electrodes, build-up of gas at electrodes, among others.

1 INTRODUCTION

The electrokinetic technique applied to the Civil and Environmental engineering field has been developed all over the world, mainly in the beginning of this century due to the insertion of new materials in this field of study (Chew et al. 2004, Jones et al. 2008). This technique is being researched from the *in situ* soils decontamination process (Lamont-Black et al. 2006) up to the technology improvement of reinforced soils. The majority of the studies are carried out in temperate-region soils, which have a default behavior.

In Brazil, where soil predominantly shows distinguish behavior, the electrokinetic technique is vastly exploited in the area of soils bioremediation. In order to follow the world's trends, as electrokinetic is being used in various areas, Nascimento (2005) started to study in Brazil the use of the electrokinetic technique for the purpose of accelerating the tropical soft soils consolidation process.

2 BACKGROUND

The treatment involves applying a direct voltage across electrodes embedded in the soil to generate electrical current in the soil. The current induces the movement of soil pore water from the anode (positive pole) towards the cathode (negative pole). Typically, the soil water is permitted to drain at the cathode and is prevented from entering the anode, which leads to soil consolidation. The electro-osmotic consolidation process decreases the soil water content and increases the soil shear strength.

There are a number of theories relating to electro-osmosis. The Helmholtz–Smoluchowski theory is the earliest and most widely used. This theory is analogous to Darcy's law of fluid flow, where the electro-osmotic flow produced by an applied electrical field is given by the expression:

$$Q_e = K_e . i_e . A \qquad (1)$$

Q_e is the electro-osmotic flow (L^3T^{-1});

K_e is the electro-osmotic conductivity ($L^2T^{-1}V^{-1}$);
A is the cross-sectional area (L^2);
i_e is the voltage gradient (VL^{-1}).

The electro-osmotic permeability coefficient is a soil property that indicates the speed of hydraulic flow under a unit electric gradient and thus is analogous to hydraulic permeability which is the flow speed under unit hydraulic gradient. It is known by experiments that K_e is usually between the interval 1 x 10^{-9} and 10 x 10^{-9} $m^2/s/V$ and it is relatively independent from soil type, but it is sensible to electrolytic water concentration. From Jones et al. (2008), the factors of the mineralogy which cause a positive effect on the potential for good electro osmotic include: high water content, clay minerals with low cation exchange capacity CEC, low valency exchange cations, high surface charge density and a high surface area, a water composition which has low conductivity (σ), low salinity, a high pH and a low surface charge density per unit pore volume A_0.

Therefore, these factors may influence electro-osmotic (EO) efficient of tropical soils because they are compounded of different mineralogy from soils that are considered as being not tropical which influences directly on the charge type of superficial particles. Both soil types show different electrochemical behavior, as the tropical soils are mostly compounded of superficial variable charge minerals because they quite vary pH and the no tropical soils are compounded by constant superficial charge minerals.

Because of the reasons mentioned before, the flow inversion can happen when the soil is submitted to a high level of weathering, in other words, the flow can occur towards the anode instead of going towards the cathode (Saichek & Reddy 2002).

3 EXPERIMENTAL INVESTIGATION

This study was carried out using the prefabricated vertical drains (PVD) overcharge conventional technique, as well as adding the antique electro-osmotic knowledge to this technique creating what is called as geosynthetic new technology. A reconstituted sample, soil tropical mixed thoroughly with a substantial amount of water treated (0 g/L) or brackish water (16.5 g/L) or seawater simulation (33 g/L), 57% of water content, was placed inside the apparatus in layers. Table 1 shows the physical characterization of the soil used in the laboratory trial.

Table 1 – Physical properties of the soil used in the laboratory trial.

CHARACT.	SOIL JC	CHARACT.	SOIL JC
Sand (%)	31.3	W_P (%)	30
Silt (%)	10.8	IP (%)	7
Clay (%)	57.6	I_A	1.94
W_L (%)	37	ρ_G (g/cm^3)	2.79

The equipment developed for laboratory trial was similar to a cell used by Dinoy (1999) with reconstructed clay from Bangkok – Thailand.

The experiments consisted on the installation of electrical conductor drains and prefabricated vertical drains in an electro-osmotic cylinder cell (Figure 1) which contained saturated soils with clean water and salt water. For the electro-osmotic trial an electric current passed by a conductor drain to another drain as an attempt to accelerate and conduct water in soil to the direction of the draining element to achieve soil consolidation. On conventional trial, the same characteristics of the prior trial were used, excepting the use of electricity. Vertical load application on the top cap is through a loading piston connected pressure camera where air pressure is being supplied by a compressor and is controlled by a valve regulator. The electro-osmotic cell can accommodate a disturbed sample up to a height of 450 mm and an inner diameter of 280 mm. All trials were monitored with strain gauges to register the settlement. Also, a vane test was executed before and after the treatment to know the increase of undrained soil shear strength.

The electrical conductor drains (ECD) were developed with the same shape of the electrically conductive geosynthetic (EKG). So, a geosynthetic which is an electrical and hydraulic conductor accepts that a simple element can be used as a electrode. An adapted PVD was developed for laboratory trials with 20mm width and was attached 6mm area copper braid as conductor material (electrode).

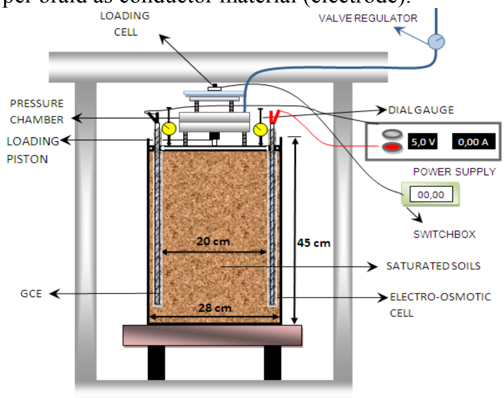

Figure 1 – Electro-osmotic cell

The electrodes were 20 cm distant from each other, as one of them was connected to the positive pole of the source turning into anode drain and the other one was connected to the negative pole turning into cathode drain. The follow planning was developed to optimize variables noticed on normal consolidation trials end by the electroosmosis:

1. Loading aplication: 50 kPa e 100 kPa
2. Different voltage gradients (DDP): 5V (25V/m), 15V (75V/m) e 25V (125V/m)
3. Electrode type: cooper
4. Concentrations of salt: 0g/L, 16,5g/L, 33g/L.

4 TEST RESULTS

The current development during the homogenized soil trials with seawater simulation (Figure 2) and brackish water (Figure 3) is displayed for better understanding soil settlement results and undrained shear strength.

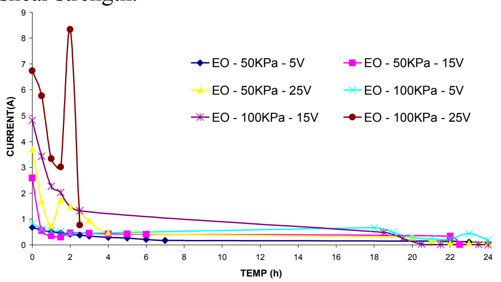

Figure 2 – Current development in trials with seawater simulation.

The graphic shows the current decreasing with not linear time form in all trials which were carried out. Current variation caused by the time occurs because of circuit variation, as the DDP applied between the electrodes is constant. From all trials carried out in this situation it was noticed that 5V trial were the only one which maintained relative current value constancy from the begging until the end of the trial.

A limitation of ECD was identified: electrodes' disruption. The total rupture of the electrodes occurred in only two trials located in anode ECDs. The water electrolysis occurred by the application of voltage which generated air bubbles in the cathode produced by hydrogen gas release. The oxygen was released as a gas in the anode, oxidizing the existing copper on the media and also producing copper hydroxide or hydrated copper oxide which are substances with greenish coloration that are found in the electrodes after the end of the trial.

On trials carried out on homogenized situation with brackish water there was no electrode rupture. Probably, because of the fact that current that passed through soil is less intense, so water electrolysis and the attack to the electrodes took more time to happen. However, the corrosion obviously happened.

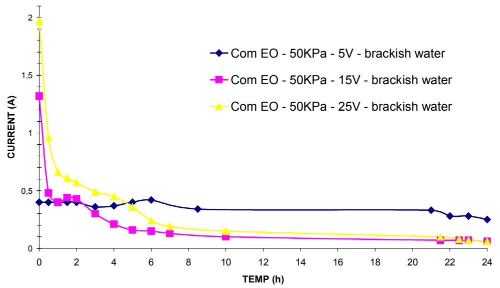

Figure 3 - Current development in trials prepared with brackish water.

On the trials carried out with brackish water it was noticed that the 5V trial (Trial 13) maintained relative current value constancy from the begging until the end and the 15V and 25V trials (Trial 14 and 15) decreased as time went by. However, all trials had the same behavior of the trials carried out with seawater.

Figures 4 and 5 show the results settlement and shear strength of homogenized soils with seawater simulation, brackish water and standard trial, in other words, without using EO (Trial 2).

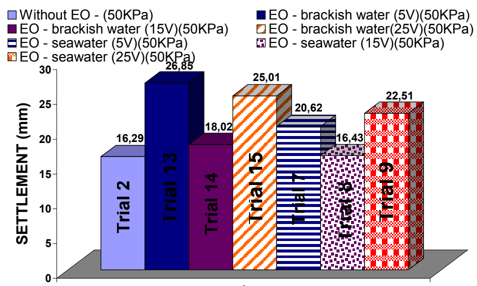

Figure 4 – Settlement results in 24 hours of experimental and electro-osmotic trials.

The explanation of the settlement obtained is based on the current development. The major settlement occurred on 5V trial (Trial 13) where the current kept itself almost constant all the time with superior value during most of the time. 25V trial (Trial 15) had a greater settlement than the 15V trial (Trial 14), because the 15V trial current development is greater in importance than that in trial 14.

Comparing the electro-osmotic trials of the Figure 4 it is noticeable that 5V trial with homogenized soil with brackish water (Trial 13) had an increase settlement 30% more when compared to the trial of same voltage with homogenized soil with seawater (Trial 7). The 5V trial really stood out with brackish water (Trial 13) – which had a 65% settlement greater than the experiment trial on the same conditions. The same behavior can be seen in Figure 5 of the undrained soil shear strength in the end of the trial. The general behavior is clearly noticed, also the 5V trial with brackish water (Trial 13) stands out again. "Trial 13" had a 170% increase on its shear strength when compared to the experimental trial on the same conditions. Therefore, tests with brackish water stood in relation to the tests with sea water, due to the constant behavior of the current and always with higher values. So, the current ruled behavior of settlement and shear strength of soil.

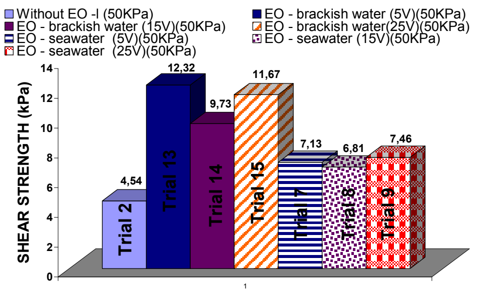

Figure 5 – Results of soils shear resistance in experimental trial and of electro-osmotic trials.

Figure 6 shows the energy consumed per volume unit from all electro-osmotic trials. It was noticed that 5V trial with 50kPa of homogenized charge with seawater (Trial 7) presents the less consumption per volume unit treated. However, the 5V trial with 50kPa charge and also homogenized with brackish water (trial 13) presents the best cost-benefit because the energy consumption per volume unit is a bit higher than that on trial 7, but this last one had settlement 30% more and it was 73% more shear strength, emphasizing the advantage in terms of cost-benefit.

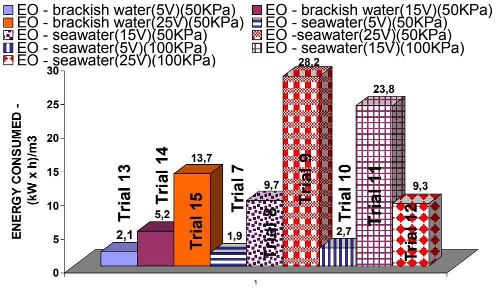

Figure 6 – Results of the energy consumed in all electro-osmotic trials.

5 CONCLUSIONS

Limitations caused by the introduction of electrodes in the drains were reported in the electro-osmotic trials, in other words, when the set of the EKG is used corrosion occurs and in consequence the rupture of the electrodes also occurs. However, it was possible to notice the behavior of electro-osmotic in different enviroment and situations when intempe-rized soils are used. Among the trials which were carried out, the 5V trial with 50kPa of charge stood out, presenting 65% higher settlement and a 170% increase in shear strength when compared to standard trials without electricity. Therefore, using an adequate voltage gradient in a middling saline media, electric current constancy is obtained and in consequence more efficiency in electro-osmotic process is also obtained, because the current governing the behavior of settlement and shear strength of soil.

REFERENCES

Chew, S. H., Karunaratne, G. P., Kuma, V. M., Lim, L. H., Toh, M. L. & Hee A. M. (2004). A field trial for soft clay consolidation using electric vertical drains. Geotextiles and Geomembranes, 22, No. 1–2, 17–35.

Dinoy A., JR. (1999) Electro-osmotic Consolidation of Reconstituted Soft Bangkok Clay with Prefabricated Vertical Drains. AIT thesis No. GE 98-5, Asian Institute of Technology, Bangkok.

Jones, C.J.F.P., Lamont-Black, J., Glendinning, S., Bergado, D., Toby, E., Fourie, A., Liming, H., Pugh, C., Romantshuk, M., Simpanen, S., Yan-feng, Z. (2008). Recente Research and Applications in the Use of Electro-Kinetic Geosynthetics. Proceedings of the 4th European Geosynthetics Conference - EuroGeo4 - Keynote Paper, 30p.

Lamont-Black, J., Huntley, D. T., Glendinning, S. & Jones, C. J. F. P, (2006a). Case history: the use of electrokinetic geosynthetics (EKG) in belt press dewatering. 8th International Conference on Geosynthetics, Yokohama, pp:535 – 538.

Nascimento, A.J.P. (2005). Acceleration of Clayey Soil Consolidation with the Use of Electro-Osmosis. Master dissertation, Publication G.DM-131/2005, Department of Civil and Environmental Engineering, University of Brasilia, Brasília, Brazil, 117 p (*in portuguese*).

Saichek, R. E.; Reddy, K. R. (2002). Effect of pH control at the anode for the electrokinetic removal of phenanthrene from kaolin soil, Chemosphere, 51, 273-278.