# An experimental study on the consolidation of soft clayey soils using electrochemical methods

## Étude expérimentale de la consolidation des argiles molles avec des méthodes électrochimiques

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ABSTRACT: An experimental study was performed where the acceleration of the consolidation using electroosmosis of normally consolidated saturated white Kaolin was investigated. The speed of consolidation was measured through the consolidation coefficient computed using the results of oedometer tests in which DC voltage was applied during the entire loading period. The inclusion of drains and electrodes in the drains was also studied in an experimental apparatus developed for this purpose. The results are interpreted and data is analyzed considering the application of this technique in practice.

RÉSUMÉ : Une étude expérimentale a été réalisée où la consolidation est accélérée en utilisant l'électro-osmose dans du Kaolin blanc saturé normalement consolidé. La vitesse de consolidation a été mesurée par le coefficient de consolidation calculé en utilisant les résultats des essais oedométriques dans lesquels la tension continue était appliquée au cours du chargement. L'inclusion des drains et des électrodes dans les drains a été également étudiée dans un appareil expérimental développé à cet effet. Les résultats sont interprétés et les données sont analysées en examinant l'utilisation de cette technique pour la pratique dans plusieurs conditions naturelles.

KEYWORDS: Electrokinetic, consolidation, water percolation, electrical technique, electroosmosis.

## 1 INTRODUCTION

Soil treatment with binders or other cementing materials, or the adoption of speed up consolidation techniques are necessary to treat soft clayey soils to make them appropriate to be used as foundation soils. Several techniques are available nowadays, such as pre-charge embankments, radial drainage, drainage with vacuum, electrochemical methods, etc, which have specific advantages/ disadvantages, variable cost and different implementation challenges. This paper focuses on the use of electrochemical methods, such as electroosmosis. Some field cases are described in the literature (see Glendinning et al., 2005, for example) and concern stabilization of slopes, excavations and embankments. Several aspects must be analyzed concerning the use of dewatering techniques based on electrochemical effects, mainly related with design, cost/efficiency and possible collateral effects.

The working principle of electrochemical methods is to apply a difference in electrical potential between electrodes placed in the soil to move the positive ions (cations) towards the negative electrode (cathode) and the negative ions (anions) towards the positive electrode (anode). These techniques are used to drain saturated soils and therefore to improve their mechanical properties, as well as for decontamination purposes. For the particular case of clay minerals, due to their negatively charged surface, they attract positive ions and immobilize them on the double layer to neutralize the electrical forces involved. Thus, a movement of cations will occur, which will carry the pore water in the same direction. The water is carried in this flow of ions in a viscous manner and, if water is drained, this will results in dewatering from the positive electrode (anode) to the negative electrode (cathode).

The work presented in this paper describes an experimental study where normally consolidated saturated white Kaolin specimens were investigated in order to understand the advantages of using electroosmosis to accelerate consolidation when compared with adopting a mesh of drains to ensure radial drainage. The last method was also included in the study because radial drainage is one of the most used methods for accelerating the consolidation of clayey soils.

The speed of consolidation was measured through the consolidation coefficient and the consolidation time necessary for a given settlement to occur. The electroosmosis method was studied in tests performed in oedometer conditions, in which DC voltage influence on settlements was analyzed. The study of radial drainage was performed in an experimental apparatus developed for this purpose. The inclusion of electrodes in the drains was also studied.

## 2 ELECTROOSMOSIS

As a technique for accelerating consolidation, electroosmosis can be studied has if it was a case of pore pressure increment, which can not cause undrained failure in the soil. Esrig (1968) studied the different types of pore pressures that can be developed in the soil mass as function of the drainage conditions. The more usual condition on consolidation by electroosmosis is assuming that drainage is performed only through the cathode electrode.

Water flow $q_h$ is given by Equation 1, where $k_e$ is the coefficient of permeability measured when water percolates only due to electroosmotic effects, $k_h$ is the coefficient of hydraulic permeability, $u$ is the excess of pore water pressure caused by electroosmosis (and/or by the increment of vertical stress) and $V$ is the voltage. This equation shows the proportionality between the voltage in the soil and the pore water pressure developed and is used to find the distribution of the pore water pressure.

$$q_h = -\frac{k_h}{k_e}\frac{\partial u}{\partial x} - k_e\frac{\partial V}{\partial x} \tag{1}$$

Equation 2 comes from introducing Equation 1 in Darcy's equation and both in the equation that governs the one-dimensional consolidation (Terzaghi et al. 1996). In Equation 2, $m_v$ is the compressibility index of the soil, $\gamma_w$ is the volumetric weight of water, $t$ is time and $c_v$ is the coefficient of consolidation. Distance $x$ is measured along the flow path, one-dimensional in this case.

$$\frac{\partial^2 u}{\partial x^2} + \frac{k_e}{k_h}\gamma_w\frac{\partial^2 V}{\partial x^2} = \frac{1}{c_v}\frac{\partial u}{\partial t} \tag{2}$$

The solution of Equation 2 is Equation 3, which is used to compute the excess of pore water pressure developed during the electroosmosis. In this equation, $V_m$ is the maximum voltage applied to the soil and $T_v$ is the time factor, which depends on the distance $L$ between the electrodes and on the time $t$, and is given by Equation 4.

$$u = -\frac{k_e}{k_h}\gamma_w V(x) + \frac{2k_e V_m}{k_h \pi^2}\gamma_w \sum_{n=0}^{\infty}\frac{(-1)^n}{A}\, sen[B]\exp\left[-A\pi^2 T_v\right] \quad (3)$$

with $A = \left(n + \frac{1}{2}\right)^2$ and $B = \dfrac{\left(n + \frac{1}{2}\pi x\right)}{L}$

$$T_v = \frac{c_v t}{L^2} \quad (4)$$

According to Mitchell and Soga (2005), the solution of Equation 3 is given by Equation 5 (parameter A given in Eq. 3) (Mitchell and Soga 2005), where $U$ is the average degree of consolidation. These authors present some abacus with the solution for several cases.

$$U = 1 - \frac{4}{\pi^2}\sum_{n=0}^{\infty}\frac{(-1)^n}{A}\exp\left[-A\pi^2 T_v\right] \quad (5)$$

In case of radial flow occurring simultaneously, Equation 2 can be converted into Equation 6, where $r$ is the distance measured in the horizontal direction, $c_r$ is the coefficient of consolidation in this direction, $x$ here is measured along the vertical direction, as well as $c_v$, and the other parameters were already explained. Mitchell and Soga (2005) also found the solution for this equation. The case voltage V=0V can also be found by solving this equation, by correcting radius $r$ to consider each drain.

$$c_r\left[\frac{\partial^2 u}{\partial r^2} + \frac{k_e}{k_h}\gamma_w\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\left(\frac{\partial u}{\partial r} + \frac{k_e}{k_h}\gamma_w\frac{\partial^2 V}{\partial r^2}\right)\right] + c_v\frac{\partial^2 u}{\partial x^2} = \frac{\partial u}{\partial t} \quad (6)$$

## 3 SOIL, EQUIPMENT AND TESTS PERFORMED

The material used in the tests is a commercial white Kaolin ($w_L$=75%, IP=40%, classified as CH). Reconstituted specimens were prepared with water content equal to 1.5 $w_L$ and were normally consolidated for a maximum stress of 12 kPa. The electrical resistivity of the saturated soil for different water contents (and therefore void ratios) was also measured in order to confirm that this parameter does not changes significantly during the performance of the oedometer tests. Further details can be found in Nogueira Santos (2012).

Some calibration tests were performed first to ensure that the oedometer equipment was isolated from the electrical system. This motivated the adoption of a PVC ring instead of a stainless steel ring, because PVC is an electrical insulator material.

A commercial 9V battery cell was adopted to apply the electrical flow to the soil. Later, a modified mobile phone battery charger was used, which is shown in Figure 1. This source has a DC voltage of 6.39V and an intensity of 0.71A and was chosen because the batteries were not able to keep constant voltage for long periods of time.

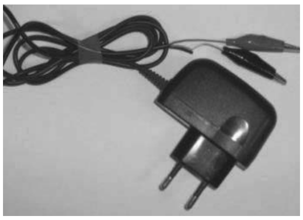


Figure 1. Modified mobile phone battery charger

Two different types of tests were performed where several different cases were tested. The specimens of the first type were tested in a normal oedometer cell adapted to apply an electrical field to the soil. Tests were performed with and without the application of electrical DC voltage and two different voltages were tested: 6.35V and 9V. The oedometric cell used was modified to include four silver electrodes (square plates) in the top and in the bottom porous stones, as shown in Figure 2.

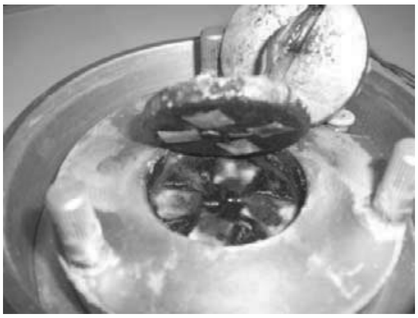


Figure 2. Silver electrodes on the porous stone

For the second type of tests a new consolidation cell was developed to include vertical drains. The spacing of the drains was designed so that radial flow would occur instead of vertical flow. This cell (120mm diameter and 70mm high) is made of acrylic and is shown in Figure 3. The top load plate of the cell was drilled to allow the inclusion of the drains and the settlement of the soil without interference. A geosynthetic material was placed between the specimen and the load plate to enable drainage from the top. The drains introduced allowed drainage by hydraulic gradients generated by the increment of vertical stress, or drainage generated by this mechanical action as well as with the application of an electrical field. The radius for the volume of soil surrounding each drain is 14mm, which allows considering that drainage occurs mainly in the radial direction. For the last case, medical needles were used as electrodes, placed inside the drains. The drains considered are the needles cases filled with fine sand shown in Figure3.

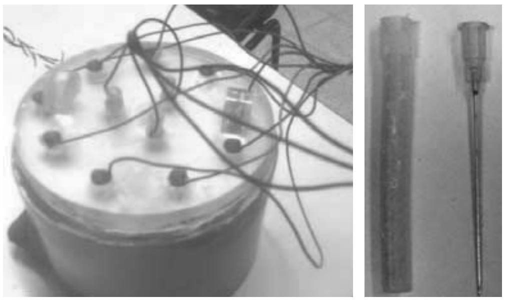
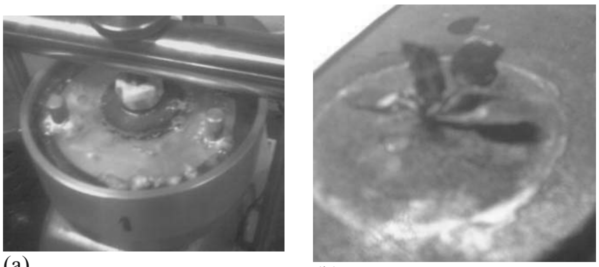


Figure 3. Apparatus for the radial flow test and detail of the drains.

Electrodes corrosion and the formation of an oxide were detected during the electroosmotic one-dimensional tests, as well as the formation of gas bubbles. Figure 4 shows some photographs of the gas formation (a) and the electrode corrosion (b). The silver oxide produced in test EO3 is shown in Figure 5. Only electrodes corrosion was observed in the electroosmotic radial flow tests.



(a) (b)

Figure 4 – (a) Gas formation (b) Electrode Corrosion.

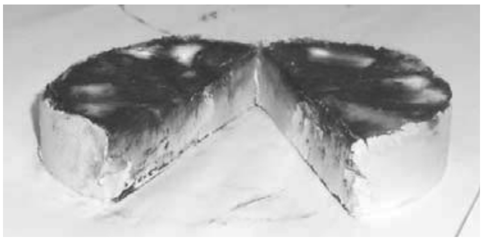


Figure 5. Silver oxide in the top of the specimen.

## 4 ONE-DIMENSIONAL CONSOLIDATION TESTS WITH ELECTROOMOSIS

Several oedometric tests were performed in order to determine the influence of the electric current in soil consolidation speed. Besides the reference test EC1, where there was no application of electrical current, the cases with electrical current allowed to study the influence of increasing voltage (EO1 with DC voltage 9V and EO2 with DC voltage 6.35V) and the influence of applying a reversible current flow (EO3 with DC voltage 6.35V). The stress path adopted was the same in all cases, consisting in increasing the vertical stress each 24h: 12kPa-25kPa-50kPa-100kPa-200kPa-400kPa-800kPa-1600kPa-400kPa-12kPa.

The influence of electroosmosis in consolidation was studied by comparing the results of tests EC1 with those of EO1 (9.0V) and EO2 (6.35V). Figure 6 shows the plot effective stress *vs* void ratio, where it can be seen that the electrical treatment applied for 24h slightly increases the magnitude of the settlements, however the compressibility characteristics of the soil are not much affected (EC1 (0V): $C_c$=0.470 and $C_s$=0.128; EO2 (6.35V): $C_c$=0.541 and $C_s$=0.146; EO1 (9.0V): $C_c$=1.135 and $C_s$=0.133).

The comparison of the results found in tests EO2 and EO1 allows understanding the influence of the applied voltage. As it can be seen in Figure 6, the use of a higher voltage for the same period of time (24h) increases the magnitude of the settlements. This is because the volume of water extracted increases.

The efficiency of the consolidation process must be measured in terms of the settlements rate instead of total settlements, in particular because, in practice, electroosmosis is applied during short periods of time because its effects are visible faster and also for reducing energy costs. This rate is measured through the coefficient of consolidation $c_v$. The main differences between the three tests are illustrated in Figure 7. As shown in this figure, this coefficient does not depend on the applied stress and is higher for the tests where the electroosmotic treatment was applied. This coefficient increases one order of magnitude when the electrical current is applied, which proves that the current accelerates in a significant manner the consolidation process.

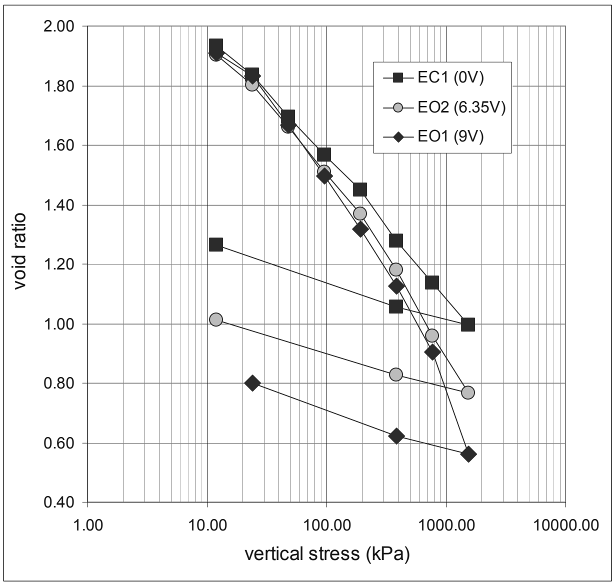


Figure 6. Effective stress vs void ratio curve for EC1, EO1 and EO2.

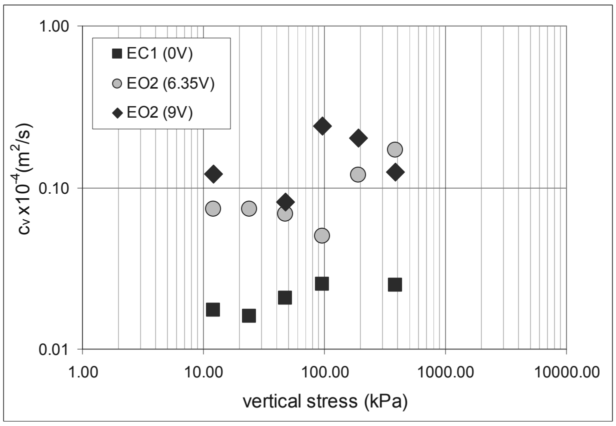


Figure 7. Coefficient of consolidation as function of the applied stress.

The comparison of the coefficients of consolidation measured in all tests presented in Figure 7 shows that the values are very similar for both tests where voltage was applied, which indicates that the increment of voltage had no significant effect in the time necessary to consolidate the soil for high consolidation degrees. This may be due to the fact that the two voltages are very similar. Further analysis on the settlements measured in these two cases, and considering the similar consolidation coefficients measured, showed that secondary settlements increase with voltage, and for this reason there is a larger reduction in void ratio for 9.0V.

Figure 8 presents the evolution of the settlements in time under the vertical stress of 50kPa (load increment of 25kPa) for the tests EC1 and EO2 (6.35V). When the two curves are compared it can be seen that the settlements measured in EC1 after 24h (at the end of the consolidation) were reached in test EO2 about 4h after the application of the load increment. It can be seen also that settlements increase in time with constant rate when electroosomosis is applied, which indicates important secondary consolidation.

To conclude, 4h was the time needed in each load step of EO2 to achieve the settlement measured in EC1 at the end of consolidation in this test. This means that consolidation using electroosmosis was about 6 times faster than in the other cases if any type of treatment is adopted. Similar values were found for each loading increment, as well as for test EO3(6.35V) where reversible current was applied for load increments with the duration of 24h each. This last test had the advantage of reducing the formation of silver oxide.

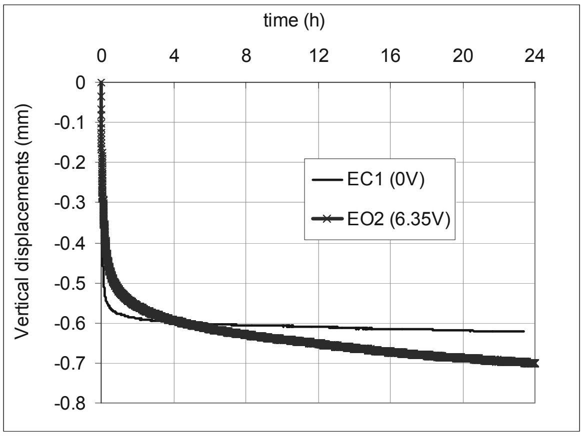


Figure 8. Evolution in time of the vertical displacements under the vertical stress of 50kPa in tests EC1 and EO2.

## 5 RADIAL CONSOLIDATION TESTS

As mentioned before, a similar study was made for the radial flow tests EOR and ER. Figure 9 is similar to Figure 8 but presents the vertical deformations measured in the tests EC1 and ER, when the vertical stress of 50kPa is applied (load increment of 25kPa). Deformations are shown instead of vertical displacements to account with the different heights of the specimens. The curve from ER test was corrected to account with the stiffness of the equipment (including drains, top geotextile and load plate). When the two curves are compared it can be seen that the deformations measured in EC1 after 24h (at the end of the consolidation) were reached in test ER about 2hours after load increment (12 times faster than if there would be no drainage). This increment is larger than the one observed when tests EC1 and EO2 are compared, which indicates that the efficiency of radial drainage in accelerating consolidation is higher than that of electroosmosis.

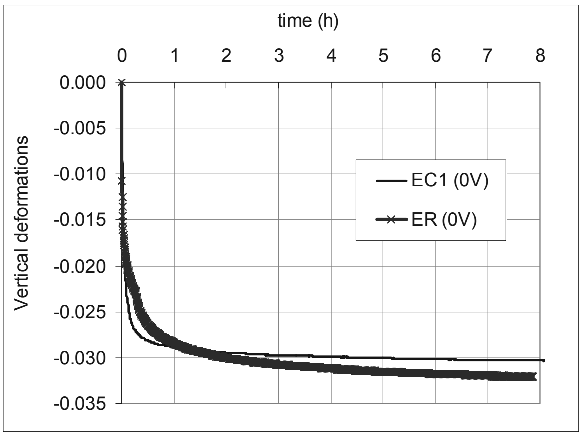


Figure 9. Evolution in time of the vertical deformations under the vertical stress of 50kPa in tests EC1 and ER.

There is no significant difference in the results found for the two tests performed with drainage in the radial direction. For the test where electrical current was applied the anode was in the exterior circle and the cathode was in the interior circle. The comparison of the values measured for the coefficient of consolidation in the radial direction ($1\text{x}10^{-4}\text{m}^2/\text{s}$, independently from the use or not of electrical current) (Nogueira Santos, 2012) and those measured in the oedometric cells presented in Figure 7 shown that the main mechanism of water drainage in these tests is through the drains because the values in radial direction are about one order of magnitude higher than those in the vertical direction. The values of the coefficient of consolidation in the radial direction slightly increase when electrososmosis occurs but the increments are not significant. This may be explained by the fact that the drains, both in anode and cathode, were left open and water could flow also as in the test where electricity was not used.

The small difference between the cases using drains with and without voltage shows that the inclusion of electrical current brings no evident earning in time savings for the particular case of radial drainage. The application of electrical current may eventually reduce the number of drains but it will affect their radial efficiency and this must be studied in the future.

## 6 CONCLUSIONS

The study presented confirms that electroosmosis accelerates the one-dimensional consolidation of clayey soils because the consolidation coefficient $c_v$ increases about one order of magnitude. This is a very significant improvement.

The studies where an electrical field was applied for 24h indicated that the settlement obtained can be larger than if there was no electrical current. For this reason the duration in time of the treatment must be controlled. For the one-dimensional consolidation tests performed, the use of electrical current allowed reducing the consolidation period in a factor of 6. Regarding the value of voltage applied to the soil, higher voltages can result in larger settlements if they are applied the same period of time. It can be deduced that the time during which voltage is applied can be reduced if high voltages are applied, as long as they are safe in the field.

Accordingly with the results of the tests with radial consolidation, considering the overlap between radial and vertical directions taken as a hypothesis for Esrig (1968), if the drains mesh is well designed, the inclusion of radial drainage direction has the most important role. Eventually, drainage in the vertical direction may not be considered.

The inclusion of radial drains without any electrical current allowed reducing the consolidation period by a factor of 16, which is 2.6 times larger than the factor found for the one-dimensional consolidation test with electroosmosis. Comparing the two techniques for accelerating consolidation, although the good results obtained when electrical current is used, the reduction achieved may not compensate the cost increment due to the energy spent with the process, as well as the need of specialists to install and control the technique. The installation of drains is proven to be efficient and economical, which explains the use of this technique in practical and current cases. Nevertheless, it is believed that the use of electroosmosis can be advantageous in Environmental Geotechnics problems and for this reason studies like the one presented will be useful to understand better the potentiality of this technique.

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