Electro-osmotic consolidation: Laboratory tests and numerical simulation

Électro-osmotique de consolidation : les tests de laboratoire et simulation numérique

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ABSTRACT: Electro-osmotic consolidation is an attractive soil improvement technique for soft clay. A review of research and practical applications of electro-osmosis was performed. The achievements and major bottleneck of the current technique were briefly discussed, and the potential areas for scientific research and engineering application were proposed. A laboratory testing facility was developed for the electro-osmotic consolidation, and the electrical voltage, soil mass displacement, water discharge and electrical current can be monitored during testing process by use of online transducers. Moreover, the microscopic phenomenon is investigated by use of Environmental Scanning Electron Microscopy (ESEM). A theoretical model for electro-osmotic consolidation is briefly introduced, which couples Biot's consolidation equation with the electro-osmotic flow and control equation for an electrical field, and incorporates the nonlinear variation of the mechanical, hydraulic and electrical properties. The FEM software was developed based on the theoretical model to describe the electro-osmotic consolidation process, and the model tests are simulated. The numerical results showed good agreement with the testing data in terms of ground settlement, indicating the rationality of the analytical model. It is also shown that the variations of electrical conductivity have a significant effect on the consolidation process. The developed software can predict the displacement behavior of soil mass and provide useful data for system design of electro-osmosis treatment.

RÉSUMÉ : La consolidation électro-osmotique est une technique attrayante d'amélioration de l'argile. Une révision des demandes de recherche et de pratique de l'électro-osmose a été effectuée. Les réussites et le goulot d'étranglement majeur de la technique actuelle ont été brièvement discutés, et les domaines potentiels de la recherche scientifique et l'application d'ingénierie ont été proposés. Un centre d'essais en laboratoire a été développé pour la consolidation électro-osmotique, et la tension électrique, le déplacement massif de sol, l'évacuation de l'eau et le courant électrique peuvent être contrôlés pendant le processus d'essai en utilisant des capteurs en ligne. En outre, le mécanisme microscopique de la migration de l'eau interstitielle et des ions est étudié par l'utilisation de microscopie électronique à balayage environnemental (ESEM). Un modèle théorique pour la consolidation électro-osmotique est brièvement présenté, qui couple l'équation de consolidation de Biot avec le flux électro-osmotique et l'équation de commande d'un champ électrique, et intègre la variation non linéaire des propriétés mécaniques, hydrauliques et électriques. Le logiciel FEM a été développé sur la base du modèle théorique pour décrire le processus de consolidation électro-osmotique, les essais sur modèle sont simulés. Les résultats numériques montrent un bon accord avec les données de test en termes de tassement du sol, indiquant la rationalité du modèle analytique. Il est également montré que les variations de la conductivité électrique ont un effet significatif sur le processus de consolidation. Le logiciel développé permet de prédire le comportement de déplacement de masse de sol et de fournir des données utiles pour la conception de systèmes d'électro-osmose.

KEYWORDS: electro-osmosis; axisymmetric test; scanning electron microscopy; theoretical model; numerical simulation

1 INTRODUCTION

Electro-osmotic consolidation provides an attractive soil improvement technique, during which flow of pore water occurs from the anode toward the cathode under the electric field in soils. The electro-osmotic consolidation technique has been used in various geotechnical engineering applications, including stabilization of slopes, excavations, and embankments, controlling groundwater flow, increasing pile capacity and the strength of clays, and dewatering tailings and sludge, meanwhile, numerous laboratory studies have been published, mostly based on soil column tests (Casagrande, 1948; Casagrande, 1983; Shang and Dunlap, 1998; Mitchell and Soga, 2005; Jones et al., 2008). Recently, the combination of electro-osmosis and vacuum preloading was investigated by means of axial-symmetric model tests (Li et al., 2009; Wu and Hu, 2012).

The theory for electro-osmosis was also developed to predicte the soil behavior during consolidation. One-dimensional analytical solutions for electro-osmotic consolidation were proposed by previous researchers (Esrig, 1968; Wan and Mitchell, 1976). The analytical solutions for 2D problems were also developed (Shang, 1998; Su and Wang, 2003; Xu et al. 2011). Lewis and Humpheson (1973) formulated a finite element model to analyze the groundwater flow in two-dimensional electric fields. Rittirong and Shang (2008) proposed a 2D finite difference model to obtain excess pore-water pressure during electro-osmosis, analyzing the subsurface settlement and undrained shear strength.

Up to now, most of the analytical solutions are based on the assumption of uniform electric field, which is not applicable for most field applications due to the complexity of electrode configuration, complicated boundary conditions and anisotropic soil properties. Furthermore, the previous model focused on predicting pore water pressure, while the ground settlement was not considered. A comprehensive numeircal model is demanded to predict the soil behavior and provide data for system design of electro-osmosis treatment.

In this paper, a laboratory testing facility for axial-symmetric model was developed for the electro-osmotic consolidation, and the electrical voltage, soil mass displacement, water discharge and electrical current were monitored during testing process by use of online transducers, and the coupled effect of mechanical, hydraulic and electrical field was discussed. A theoretical model was birefly introduced (Hu et al., 2012), and FEM software was developed based on the theoretical model to describe the electro-osmotic consolidation process. The software was verified by comparison of numeical results and test data. The ESEM tests were conducted to observe the change of soil particles.

2 TEST ON ELECTRO-OSMOTIC CONSOLIDATION

An axial-symmetrical electro-osmosis apparatus made of plexiglas with a radius of 18.8 cm and a height of 20 cm shown in Fig. 1 is developed to conduct the electro-osmotic consolidation test on kaolin clay. The radius of the central cylindrical drainpipe with many small holes on it is 1.25 cm. After convolving a piece of geotextile that only water can pass through, an iron wire is then convolved on the geotextile in a spiral form to be the cathode. The anode consists of many vertical iron wires inserted in the soil sample and cling to the inner surface of the apparatus. A set of monitoring device is also developed to measure voltage distribution, water discharge, surface settlement and current during the electro-osmotic consolidation. A vacuum pump and a gas-water separation device are used to collect the water discharged from the soil sample. A multimeter is installed in the circuit to monitor the current.

The basic properties of the kaolin clay used in the test are listed in Table. 1.

After filling the test device with saturated kaolin clay, an intermittent DC electric filed shown in Fig. 2 was applied to the soil sample. The total testing time was 100 hours and the conduction time was 57 hours.

Table 1 Basic property of kaolin clay

Initial water content, *w*/%	Degree of saturation, S/(%)	Liquid limit, w_L/(%)	Plastic limit, w_P/ (%)	Specific gravity, G_s
100	100	73	31	2.61

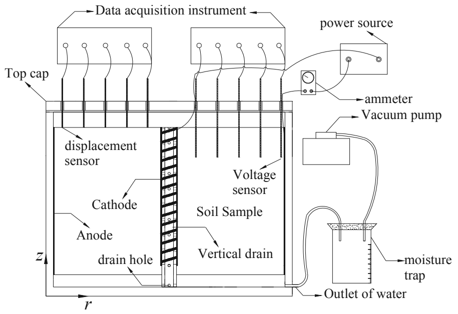


Figure 1. Testing facility for electro-osmotic consolidation

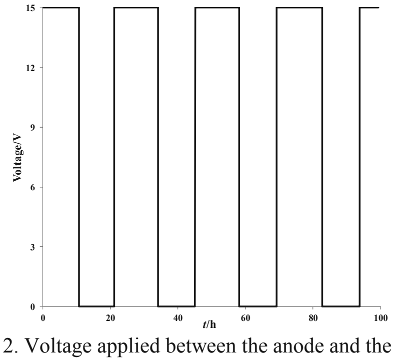


Figure 2. Voltage applied between the anode and the cathode

Fig. 3 shows the voltage distribution along the radial direction during the electro-osmotic consolidation. In most of the previous study, the voltage was supposed to be steady and linear. However, the test result illustrates that the voltage first increases with time with the largest increase near the cathode and the smallest increase near the anode. This is mainly caused by the change of soil resistance near the cathode. Along with the electro-osmosis, the soil near the cathode began to seperate from the electrode so that the soil resistance near the cathode increased, which then resulted the increase of the voltage neer the cathode. After 10 hours, the voltage began to decrease and finally the voltage near the cathode was even smaller than that at the beginning. During the electro-osmotic consolidation, the pore water moved from the anode to the cathode and some cracks gradually generated near the anode, which made the soil resistance near the anode to increase, and this further resulted the decrease of the voltage near the cathode. Therefore, the electrical conductivity changes with time and position and it is important to consider this change in the theoretical and numerical analysis.

The current across the soil mass is shown in Fig. 4 with an initial value of 0.72 A, and decrease to about 0.21 A finally. The discharge of water is demonstrated in Fig. 5 and 2294 ml water was discharged in total. When the power was switched off, the current decreased to 0 and the drainage speed almost decreased to 0. When the power was once again turned on then, the movement of the pore water was accelerated and the current first increased and after it decreased again. This was because the pore water flowed back from the anode to the cathode under hydraulic gradient after the current was cut down, which made the moisture distribution to be more uniformity and the resistance therefore decreased.

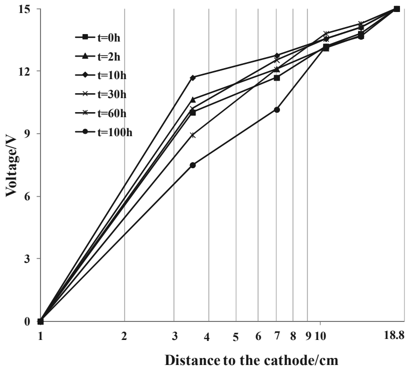


Figure 3. Distribution of the voltage along the radial direction

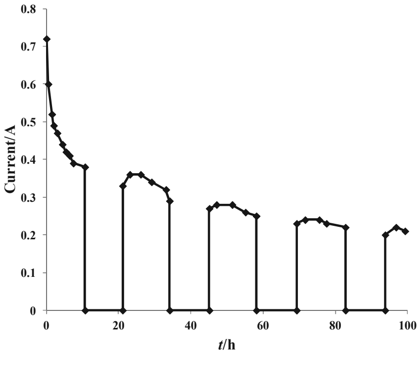


Figure 4. Current during electro-osmotic consolidation

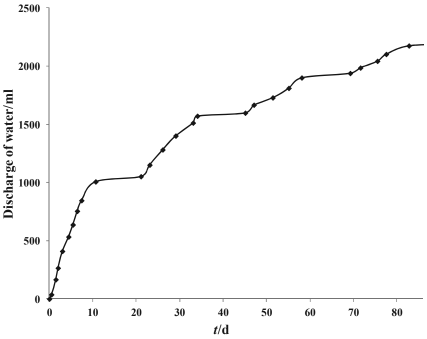


Figure 5. Discharge of water during electro-osmotic consolidation

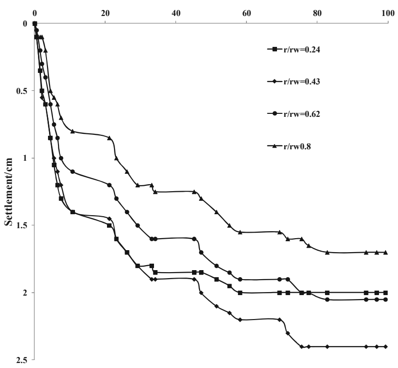


Figure 6. Surface settlements of the soil sample

The surface settlement is shown in Fig. 6. Esrig's theory about excess pore water pressure indicates that the largest settlement happens near the anode since the largest excess pore water pressure is occurred there. However, Fig. 6 shows that the largest surface settlement occurred in the middle of the two electrodes with a value of about 2.4 cm. The friction of the test device and the soil at the anode is the main reason for this phenomenon.

The test results shows that the soil parameters vary during the electro-osmotic consolidation processes, and the previous analytical solution could not adequately predict the soil behavior due to the complicated coupling effects. The multi-physics theoretical model was developed by the authors, by means of coupling soil deformation, pore water flow and electrical field (Hu et al., 2012).

3 THEORETICAL MODEL

During electro-osmotic consolidation, the pore-water flow, soil mass deformation, and electricity have a coupling effect on soil behavior.

3.1 *Coupled pore water flow*

Pore-water flow is due to the hydraulic and electrical gradients. The pore water velocity in radial and vertical directions can be described according to the Darcy's law and electro-osmotic flow theory (Esrig, 1968),

$$\begin{aligned} v_r &= -k_{\mathrm{r}} \frac{\partial H}{\partial r} - k_{\mathrm{er}} \frac{\partial V}{\partial r} \\ v_z &= -k_{\mathrm{z}} \frac{\partial H}{\partial z} - k_{\mathrm{ez}} \frac{\partial V}{\partial z} \end{aligned} \tag{1}$$

in which V and H are the electric potential and total head, respectively; v_{r} and v_{z} are the pore-water flow velocity; k_{r} and k_{z} are the hydraulic conductivity in the radial and the vertical direction; k_{er} and k_{ez} are the coefficient of electro-osmotic conductivity in the radial and the vertical direction, respectively.

For a saturated soil system with non-compressive pore-water and soil particles, the pore-water flow induces the volume strain of soil mass, i.e., consolidation of the soil skeleton. Using the law of conservation of mass for pore water, the following equation can be derived,

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = -\frac{\partial \varepsilon_{\mathrm{v}}}{\partial t} \tag{2}$$

in which ε_{v} is the volume strain of soil mass.

Therefore the governing equation for the pore water movement in the soil mass can be obtained,

$$\begin{aligned} &\frac{1}{r}\left(k_{\mathrm{r}} \frac{\partial H}{\partial r} + k_{\mathrm{er}} \frac{\partial V}{\partial r}\right) + k_{\mathrm{r}} \frac{\partial^2 H}{\partial^2 r} + k_{\mathrm{er}} \frac{\partial^2 V}{\partial^2 r} + k_{\mathrm{z}} \frac{\partial^2 H}{\partial^2 z} + k_{\mathrm{ez}} \frac{\partial^2 V}{\partial^2 z} \\ &= -\frac{\partial}{\partial t}\left(\frac{\partial u^{\mathrm{s}}}{\partial r} + \frac{\partial w^{\mathrm{s}}}{\partial z}\right) \end{aligned} \tag{3}$$

3.2 *Static equilibrium for soil mass*

The elastic constitutive model was used to reflect the relationship of the stress and the strain of the soil skeleton. Therefore, the governing equations can be obtained from Biot's theory and the effective stress principle as,

$$\begin{cases} \frac{\partial}{\partial r}\left(c_1 \frac{\partial u^{\mathrm{s}}}{\partial r} + c_2 \frac{\partial w^{\mathrm{s}}}{\partial z}\right) + \frac{\partial}{\partial z}\left[c_3\left(\frac{\partial u^{\mathrm{s}}}{\partial z} + \frac{\partial w^{\mathrm{s}}}{\partial r}\right)\right] + \frac{c_3}{r}\frac{\partial u^{\mathrm{s}}}{\partial r} = \gamma_{\mathrm{w}} \frac{\partial H}{\partial r} \\ \frac{\partial}{\partial z}\left(c_1 \frac{\partial w^{\mathrm{s}}}{\partial z} + c_2 \frac{\partial u^{\mathrm{s}}}{\partial r}\right) + \frac{\partial}{\partial r}\left[c_3\left(\frac{\partial u^{\mathrm{s}}}{\partial z} + \frac{\partial w^{\mathrm{s}}}{\partial r}\right)\right] + \frac{c_3}{r}\frac{\partial w^{\mathrm{s}}}{\partial r} = \gamma_{\mathrm{w}} \frac{\partial H}{\partial z} + \gamma'_{\mathrm{s}} \end{cases} \tag{4}$$

in which c_1, c_2, c_3 are the constant parameters only related to the young's modulus and the poisson's ratio; u^{s} and w^{s} are the radial and the vertical displacements; γ'_{s} denotes the submerged unit weight.

3.3 *Conservation of electrical charge*

According to the law of conservation of electrical charge the governing equation for the electric field can be represented by the following equation,

$$\begin{aligned} &\sigma_{\mathrm{er}}\left(\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r}\right) + \sigma_{\mathrm{ez}} \frac{\partial^2 V}{\partial z^2} + \sigma_{\mathrm{hr}}\left(\frac{\partial^2 H}{\partial r^2} + \frac{1}{r}\frac{\partial H}{\partial r}\right) \\ &+ \sigma_{\mathrm{hz}} \frac{\partial^2 H}{\partial z^2} = C_{\mathrm{p}} \frac{\partial V}{\partial t} \end{aligned} \tag{5}$$

in which C_{p} is the capacitance per unit volume; σ_{er} and σ_{ez} are the electric conductivity in the radial and vertical direction. σ_{hr} and σ_{hz} are the streaming electric conductivity in the radial and vertical direction, which denotes the current density caused by a unit hydraulic gradient.

4 NUMERICAL SIMULATION

Based on the equation (3) ~ (5), an axisymmetric electro-osmotic consolidation model was developed and the size is the same as the test apparatus. The relationship between the electrical conductivity and the void ratio is conducted from laboratory test results as (Wu, 2009),

$$\sigma_{\mathrm{e}} = 1.016 \times \left(\frac{e}{1+e} - 0.349\right) \text{ (S/m)} \tag{6}$$

The soil parameters used in the numerical model are adopted according to the basic physical properties tests on the soil sample and are shown in Table. 2 (Wu, 2009).

Table 2. Parameters adopted in the numerical model

Initial water content, w/(%)	100
Saturation, S/(%)	100
Hydraulic conductivity, k_{r}、k_{z}/(m・s^{-1})	8×10^{-10}
Electro-osmosis conductivity, k_{er}、k_{ez}/ (m^2・s^{-1}・V^{-1})	8.5×10^{-9}
Electrical conductivity, σ_{er}、σ_{ez}/ (1・ohm^{-1}・m^{-1})	0.38
Young's module, E / (kPa)	2×10^{6}
Poisson's ratio, ν	0.3

Fig. 7 shows the comparison of the surface settlement obtained from the numerical results and the experiment data. The surface settlement at the position of r/r_{e}=0.62, in which r_{e} is the radius of the model, is compared since the settlement at other positions are largely influenced by the test apparatus.

The settlement obtained from the numerical model which considered the variation of the electrical conductivity is smaller than that obtained from another numerical model in which the electrical conductivity keeps constant. The result of the model with variable electrical conductivity agrees better with the experimental data than the model with constant electrical conductivity during the consolidation process.

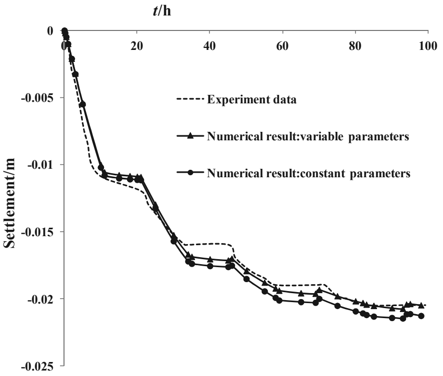
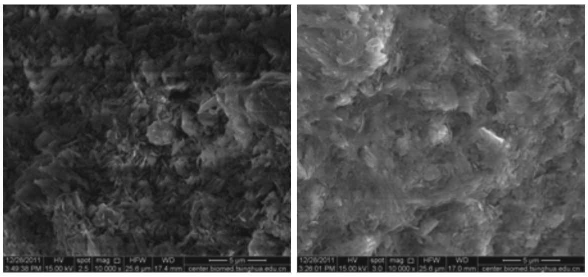


Figure 7. Comparison of the numerical model with the experimental data

5 MICROSCOPIC OBSERVATION

The scanning electron microscopy tests of the soil samples before and after electro-osmosis were conducted and the comparison was shown in Fig. 8.

Fig. 8 illustrates that after the electro-osmosis treatment, the shape of soil particles changed. The content of spherical particle and flaky particle decreased, and the content of acicular particle increased, which mean that under the application of the voltage, the soil particles broke from spherical particle or flaky particle to acicular particle.



(a) After electro-osmosis (b) Before electro-osmosis

Figure 8. Results of the scanning electron microscopy test.

6 SUMMARY AND CONCLUSIONS

The electro-osmotic consolidation process is investigated by means of laboratory test and numerical simulation. The following conclusions can be obtained based on this study.

A laboratory testing facility was developed for the electro-osmotic consolidation, and the electrical voltage distribution, soil mass displacement, water discharge and electrical current were monitored during the testing process. The coupled effect of mechanical, hydraulic and electrical field, as well as the nonlinear variation of soil resistance during electro-osmosis was observed.

A theoretical model for electro-osmotic consolidation is briefly introduced, and FEM software was developed based on the theoretical model to describe the electro-osmotic consolidation process.

The numerical results showed good agreement with the testing data in terms of ground settlement, indicating the rationality of the analytical model. It is also shown that the variations of electrical conductivity have a significant effect on the consolidation process and the numerical model which considered the variation of the electrical conductivity agrees better with the experemental data than the model with constant electrical conductivity.

The developed software can predict the displacement behavior of soil mass and provide useful data for system design of electro-osmosis treatment.

The result of the ESEM test shows that the soil particles break from spherical particle or flaky particle to acicular particle because of the applied voltage.

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