Experimental and Numerical Study of Electro-Osmosis on Kaolinite under Intermittent Current

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ABSTRACT: Electro-osmosis has been used as an effective technique for soft ground improvement. An axisymmetric testing apparatus was developed to study the dewatering and consolidation behaviour of kaolinite samples with different initial water content during electro-osmosis under intermittent current. An axisymmetric numerical model with non-linear variation of soil parameters was developed to compare with the experiment results. With the increase of the initial water content, the electrical resistance decreased and the current through the kaolin samples increased. As a result, the total water discharge and the final surface settlement also increased. The comparison of the experiment results and numerical results validated the effectiveness of the numerical model. The change in soil parameters should be considered during electro-osmosis, otherwise the final surface settlement may be over-estimated. The formation of cracks and the friction between the soil mass and apparatus caused the deviation between experiment results and numerical results.

KEYWORDS: electro-osmosis, initial water content, intermittent current, numerical model, surface settlement.

1. INTRODUCTION

Electrical induced phenomena in a porous media, including electro-osmosis, electrophoresis and electro-migration have been used extensively in civil engineering for the treatment of soft soil and contaminated soil or groundwater (Bjerrum et al. 1967; Esrig 1968; Wan and Mitchell 1976; Casagrande 1983; Lo and Ho 1991; Lefebvre and Burnotte 2002; Burnotte et al. 2004; Cameselle and Reddy 2012; Hu et al. 2012; Wu and Hu 2013; Hu and Wu 2014). With an electrical field applied to a soft soil, the pore water moves from the anode to cathode, leading to the consolidation of the soil mass. Since the electro-osmosis conductivity, which describes the transport velocity of pore liquid under a unit intensity of electrical field, is generally in the range of 1×10^{-5} to 1×10^{-4} $cm^2/(V{\cdot}s)$ for most soils, electro-osmosis is much more efficient than other soil improvement techniques.

A great number of laboratory experiment apparatus have been developed to conduct one-dimensional and aixsymmetric model tests to investigate the dewatering behaviour of soft soil during electro-osmosis (Esrig and Gemeinhardt 1967; Lockhart 1983; Micic et al 2001; Cherepy and Wildenschild 2003; Hong et al 2009; Li et al 2009; Hu et al 2010; Jiao et al 2011). Casagrande (1983) investigated the effect of electrode material, electrode installation, electrode depth and space to the dewatering process. Lockhart (1983) studied the influence of voltage, clay type, exchangeable cations and electrode material. Micic et al. (2001) reported that the power consumption and electrode corrosion were reduced by using intermittent current. Hu et al. (2010) conducted electro-osmosis experiments on kaolinite samples with different dry densities. On the other hand, the theory for electro-osmosis was also developed to predict the pore water pressure and displacement of soil mass during the treatment (Esrig 1968; Lewis and Humpheson 1973; Shang 1998; Su and Wang 2003; Rittirong and Shang 2008; Wu 2009; Xu et al 2011; Hu et al. 2012; Wu and Hu 2013; Hu and Wu 2014). Esrig (1968) proposed a 1D analytical solution to calculate the water pressure. Lewis and Humpheson (1973) formulated a finite element model to analyze the groundwater flow in two-dimensional electric fields. Su and Wang (2003) developed a 2D theoretical model in horizontal plane and gave the analytical result to predict the development of water pressure. 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. Wu (2009) coupled the seepage, stress and strain, and electrical fields together and developed a 3D theoretical model with the variation of the mechanical and electrical properties considered. However, the effectiveness of these analytical solutions and numerical models need to be further validated by experiment results.

The main purpose of this paper was to study the influence of the initial water content on the electro-osmosis process. Three axisymmetric model tests were conducted in a self-designed apparatus on kaolin samples with initial water content varied from 50% to 140%. The water discharge, voltage distribution, current and surface settlement were measured. An axisymmetric numerical model for electro-osmotic consolidation was described and the numerical results were compared with the test results for verification.

2. MATERIALS AND EXPERIMENTS

2.1 Materials

A kaolinite from Suzhou, Jiangsu Province, China was chosen for electro-osmosis experiments. Table 1 summarizes its basic geotechnical properties.

Table 1 Basic geotechnical properties of the kaolinite

Property	Value
Water content /%	0.89
Liquid limit /%	73
Plastic limit /%	31
Plasticity index /%	42
Specific gravity	2.61

2.2 Test apparatus

An axisymmetric model made of plexiglass with a radius of 18.8cm and a height of 30cm was developed for electro-osmosis experiment (Figure 1). The radius of the central cylindrical drainpipe was 1.25cm. Many small holes with radii of 2mm were drilled on the central drainpipe for the discharge of pore water. A piece of geotextile was convolved on the drainpipe to prevent the soil from squeezing out. An iron wire was used as cathode and convolved on the geotextile in a spiral form. The anode consisted of 32 vertical iron wires, which were inserted around the soil sample as shown in Figure 1. During the electro-osmosis process, the pore water was driven to the central drainpipe and discharged through the small holes, and then flowed into the bottom reservoir. The bottom reservoir was connected to a moisture trap through the bottom drainage pipe. A vacuum pump was used to pump the discharged water into the moisture trap for measurement. A set of monitoring devices were also developed to measure the real-time voltage distribution and surface settlement during the electro-osmosis. The places of the voltage and displacement sensors are displayed in Figure 1. A multimeter was installed in the circuit to monitor the current through the soil mass.

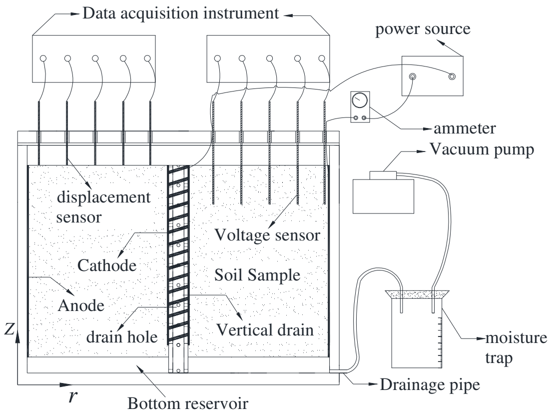

Figure 1 Axisymmetric model for electro-osmosis experiment

2.3 Experiment methods

Saturated kaolin samples with an initial water content of 140%, 100% and 50% were prepared for the electro-osmosis experiment, and the three experiments were marked as T1, T2 and T3 respectively. The radius of the kaolin samples, *R*, was 18.8 cm and the height was 20 cm. The intermittent DC electric filed for T1 is shown in Figure 2. The electric fields for T2 and T3 were almost the same as that for T1, with a little different in the time for the interruption of the power source. The experiments lasted 110 hours and the duration of power on during the intermittent current was 70 hours for the three experiments.

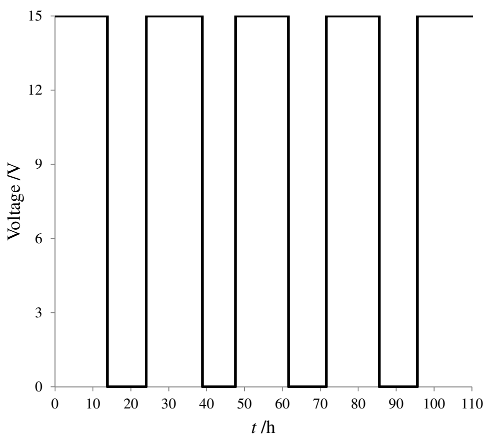

Figure 2 Applied voltage to the soil samples

3. RESULTS AND DISSCUSSION

3.1 Water discharge

Figure 3 illustrates the water discharge during electro-osmosis in the three experiments. The total water discharge were 4135, 2294, and 821 ml for T1, T2, and T3 respectively. The amount of pore water discharged from the kaolin sample decreased with the decrease of the initial water content, and this was similar to the results of Hu et al. (2010). With the decrease of the initial water content, the current through the soil sample decreased because the electrical conductivity of soil particle was much smaller than that of water (Figure 4). For T1, about 340 ml water was discharged during the first time interruption of the current, and this was mainly caused by gravity as the water content was much higher than the liquid limit in T1. After that, almost no water was discharged by gravity. For T2 and T3, the water discharge during current interruption was always 0.

Figure 4 also showed that every time the power was turned on after interruption, the current increased first and then decreased, especially for T2. The increase of current was due to the increase of soil's electrical conductivity during the interruption period, which was a result of the back flow of pore water from the cathode to the anode. The increase of current induced better drainage effect and made the current intermittence technique less power consumption and electrode corrosion.

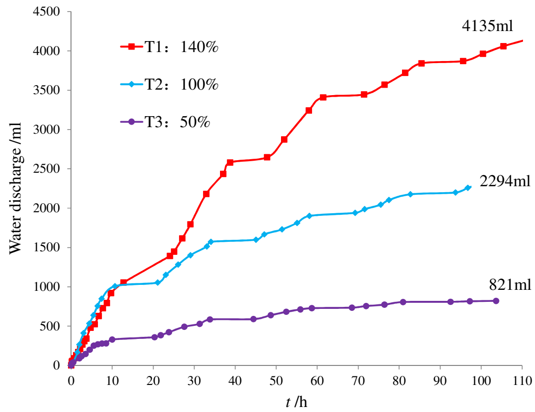

Figure 3 Water discharge during electro-osmosis

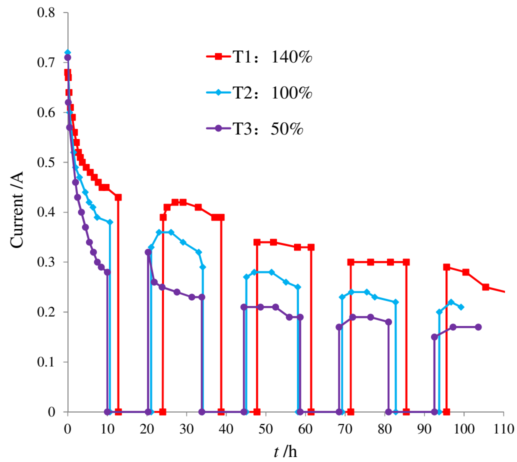

Figure 4 Current change during electro-osmosis

The surface settlement during electro-osmosis is shown in Figure 5. The four displacement sensors were 4.7, 8.2, 11.7, and 15.2 cm away from the central cathode. Therefore, the normalized distance of the four displacement sensors from the cathode were 0.25, 0.44, 0.62, and 0.81 respectively. T1 showed largest surface settlement and T3 showed the smallest. Similar to the water discharge, the surface settlement also decreased with the decrease of the initial water content. According to the previous analytical theory (Esrig 1968; Wan and Mitchell, 1976), the largest pore water pressure generated at the anode and therefore the settlement at the anode was the largest and decreased to the cathode. However, the results showed that the largest surface settlement occurred at the middle section between the anode and cathode, with a value of about 3.8cm, 2.4cm, and 0.9cm for T1, T2 and T3. One of the reason for the different settlement distribution was the friction between the soil sample and the test apparatus, which prevented the soil near the anode from free settling.

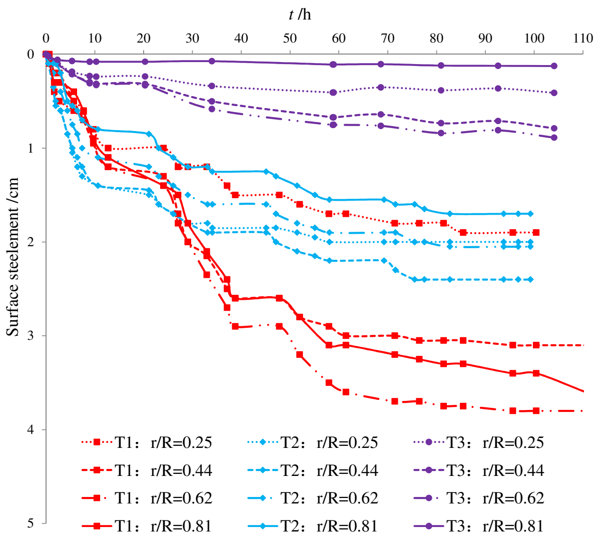

Figure 5 Surface settlement during electro-osmosis

4. NUMERICAL SIMULATION

During electro-osmosis, the pore-water flow, soil mass deformation, and electricity have a coupling effect on soil behavior. A 2D axisymmetric numerical model was developed with the seepage, stress and strain, and electrical field coupled together.

4.1 Flow of pore water

Under an applied electrical field, both the hydraulic and electrical gradients induce the flow of pore water. The velocity in radial and vertical directions can be described according to the Darcy's law and electro-osmotic flow theory (Esrig, 1968),

$$\begin{aligned} v_r &= -k_r \frac{\partial H}{\partial r} - k_{er} \frac{\partial V}{\partial r} \\ v_z &= -k_z \frac{\partial H}{\partial z} - k_{ez} \frac{\partial V}{\partial z} \end{aligned} \qquad (1)$$

in which V and H are the electric potential and total water 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 electro-osmosis conductivity in the radial and the vertical direction.

For a saturated soil system with non-compressive pore-water and soil particles, the pore-water flow induces the volume change 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,

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = -\frac{\partial \varepsilon_v}{\partial t} \qquad (2)$$

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,

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

4.2 Static equilibrium

According to Biot's theory (1941), the governing constitutive equation between stress and strain can be written as,

$$\begin{cases} \frac{\partial}{\partial r}(c_1 \frac{\partial u^s}{\partial r} + c_2 \frac{\partial w^s}{\partial z}) + \frac{\partial}{\partial z}[c_3(\frac{\partial u^s}{\partial z} + \frac{\partial w^s}{\partial r})] + \frac{c_3}{r}\frac{\partial u^s}{\partial r} = \gamma_w \frac{\partial H}{\partial r} \\ \frac{\partial}{\partial z}(c_1 \frac{\partial w^s}{\partial z} + c_2 \frac{\partial u^s}{\partial r}) + \frac{\partial}{\partial r}[c_3(\frac{\partial u^s}{\partial z} + \frac{\partial w^s}{\partial r})] + \frac{c_3}{r}\frac{\partial w^s}{\partial r} = \gamma_w \frac{\partial H}{\partial z} + \gamma'_s \end{cases} \qquad (4)$$

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.

4.3 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,

$$\begin{aligned} &\sigma_{er}(\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r}) + \sigma_{ez}\frac{\partial^2 V}{\partial z^2} + \sigma_{hr}(\frac{\partial^2 H}{\partial r^2} + \frac{1}{r}\frac{\partial H}{\partial r}) \\ &+ \sigma_{hz}\frac{\partial^2 H}{\partial z^2} = C_p \frac{\partial V}{\partial t} \end{aligned} \qquad (5)$$

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.

4.4 Non-linear change of soil parameters

Previous studies demonstrated that the mechanical and electrical properties of soil mass change during the electro-osmosis process. During the consolidation of soil mass, the coefficient of consolidation may be assumed constant, therefore the non-linear change of the electro-osmosis conductivity and electrical conductivity are considered in the numerical simulation. Wu (2009) obtained the relationships between the two parameters and the void ratio of soil as,

$$\begin{cases} \sigma_e = \sigma_{e0} \times \left(\frac{e}{1+e} \text{-}0.349\right) \ \text{(S/m)} \\ k_{er} = k_{er0} \times \frac{e}{1+e} \ \text{(m/d)} \end{cases} \qquad (6)$$

in which σ_{er0} and k_{er0} are coefficient for the electro-osmosis conductivity and electrical conductivity, and e denotes the void ratio.

4.5 Numerical results

The soil parameters used in the numerical model are listed in Table 2.

Table 2 Soil parameters used in the numerical model

Property	Value
Hydraulic conductivity, k_r、k_z /(m · s^{-1})	8×10^{-10}
Coefficient for the electro-osmosis conductivity, k_{er0} /(m · s^{-1})	1.1×10^{-8}
Coefficient for the electrical conductivity, σ_{er0} /(S · m^{-1})	1.016
Young's Module, E / (kPa)	2×10^{6}
Poisson's ratio, v	0.3

Since the surface settlement close to the wall of the apparatus was restrained, the result in the middle section (r/R=0.62) was used for comparison with the numerical result as shown in Figures 6, 7, and 8 for T1, T2, and T3 respectively. Both the numerical results with and without the variation of soil parameters were plotted in the figures.

When the variation of soil parameters (electro-osmosis conductivity and electrical conductivity) was considered in the numerical model, the surface settlement decreased as shown in Figures 6, 7 and 8. For T1, the numerical result was almost the same as the experiment result. However, after about 50 hours, the numerical results were larger than that obtained from experiment. The main reason was the formation of cracks near the electrode, which further increased the electrical resistance and caused the decrease of current. For T2, the numerical results were smaller than the experiment result in the first 30 hours. After that, the experiment data coincided well with the numerical result with the variation of soil parameters considered. The numerical result with constant soil parameters actually over estimated development of surface settlement. With the dewatering and consolidation of soil during electro-osmosis, the void ratio decreased and therefore the electro-osmosis conductivity and electrical conductivity decreased. As a result, the dewatering ratio decreased and finally a smaller surface settlement was obtained.

For T1 and T2, the experiment result was close to the numerical results, while for T3, the surface settlement was much smaller in the experiment than that in the numerical simulations. The possible reason was that for a soil mass with low water content, the friction between soil and apparatus was large enough to influence the surface settlement in the middle section.

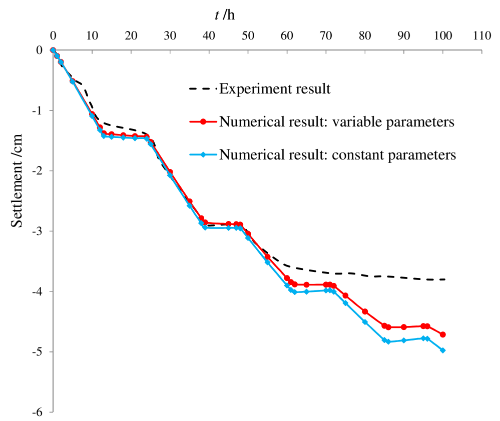

Figure 6 Surface settlement from experiment and numerical simulation (T1)

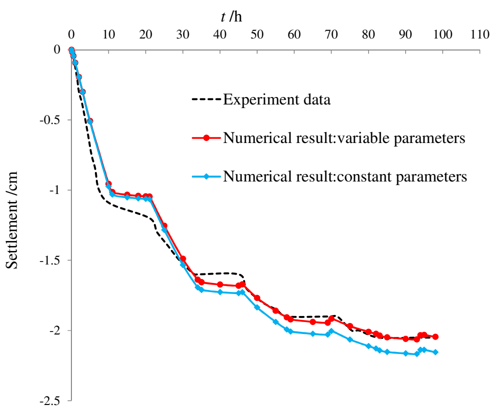

Figure 7 Surface settlement from experiment and numerical simulation (T2)

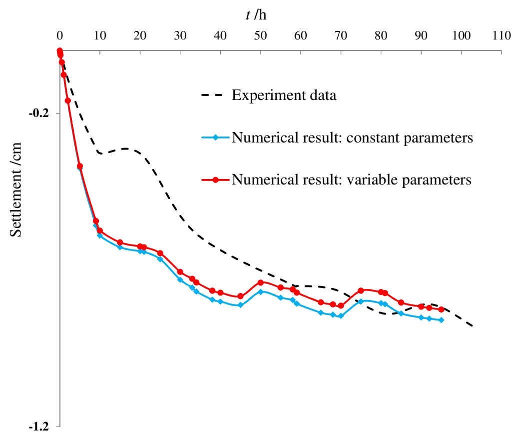

Figure 8 Surface settlement from experiment and numerical simulation (T3)

5. CONCLUSION

Three axisymmetric experiments were conducted on a kaolinite to study the effect of initial water content on the dewatering and consolidation behaviour during electro-osmosis. An axisymmetric numerical model coupling the seepage, stress and strain, and electrical fields together was developed with the non-linear variation of soil parameters considered to compare with the experiment results.

The kaolin sample with higher initial water content showed larger current and therefore larger water discharge and surface settlement during electro-osmosis. The intermittent current could improve the drainage effect because of the temporary increase of current when the power turned on after interruption.

The numerical model could predict the development of surface settlement correctly, especially when the non-linear variation of electro-osmosis conductivity and electrical conductivity was considered. However, the numerical results were larger than the experiment results at the late period because of the formation of cracks. The friction between the soil mass and apparatus restrained the development of settlement and caused the deviation between the numerical and experimental results in the early stage.

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