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Consolidation of marine clay using electrical vertical drains

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Abstract. Electroosmosis (EO) is the movement of water in a porous medium under the influence of a direct current (dc). In past decades, electro-osmosis has been successfully employed in many soil improvement and other geotechnical engineering projects. Metal electrodes, such as steel, copper and aluminum have been used traditionally to conduct current. The shortcoming of these electrodes is that they corrode easily during an EO treatment, which results in reduced effectiveness and environmental concerns. More recently, conductive polymers are developed to replace metal electrodes in EO treatment. Electrical vertical drainages (EVDs) are one of these products under trial. The goal of this study is to assess the performance of EVDs for soil improvement and to further understand the scientific principle of the EO process, including the voltage drop at the soil-EVD interface, electrical current density, polarity reversal, and changes in soil physico-chemical properties generated by electroosmosis. It is found from the study that after 19 days of EO treatment with a constant applied dc electric field intensity of 133 V/m, the soil's moisture content decreased by 28%, the shear strength and pre-consolidation pressure increased more than 400%. It is also found that the current density required triggering the water flow in the soil tested, the Korean Yulchon marine clay, is 0.7 A/m^2. The project demonstrates that EVDs can serve as both electrodes and drains for soil improvement in short term. However, the EVDs, as tested, are not suitable for polarity reversal in EO treatment and their service life is limited to only 15 days.

Keywords: Soil improvement; land reclamation; electroosmotic consolidation; electrical vertical drains.

1. Introduction

Soil improvement is often required in construction projects where soil conditions are inadequate for the foundation. The goal of the improvement includes, for example, increasing the soil shear strength and pre-consolidation pressure, and decreasing the soil void ratio and compressibility. Recent developments in land reclamation in Southeast Asia and along the Pacific Rim have increased the demand for construction on soft ground. Furthermore many offshore platforms for petroleum production have been founded on soft marine sediment. Soils encountered in these practices typically have high moisture contents, high compressibility and low shear strengths, which posts challenges in the foundation design.

Prefabricated vertical drains (PVDs) are commonly used for improvement of soft clays. PVDs consist of geosynthetic drainage cores and filters to accelerate consolidation. A surcharge fill is

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often required, which generates excess pore pressure in soil that dissipates through PVDs. The net results are the increase in the soil shear strength and decrease in the compressibility.

Electroosmosis (EO) has been used for soil improvement for decades since 1939 (Casgrande 1952). It has been employed in geotechnical engineering applications with different electrode materials and layouts (Cassagrande 1952, 1983, Shang *et al.* 1995, Hamir *et al.* 2001, Mohamedelhassan and Shang 2003, Chew *et al*. 2003, Tyagi 2005, Glendinning *et al*. 2005, 2006). In the meantime, theoretical development was made to explain the mechanical and electrochemical processes during the electro-osmotic treatment (Esrig 1968, Wan and Mitchell 1976, Shang 1997, 1998, Alshawabkeh *et al*. 2002, Micic *et al.* 2001, 2002, Shang *et al.* 1995).

More recently, electrical vertical drains (EVDs) have been developed to combine the benefit of soil improvement by PVDs and electro-osmosis (US Patent 6,089,788, 2000). EVDs have the same geometric configuration and drainage function as PVDs, but its drainage core is made of a conductive polymer entrapped with a copper foil (Fig. 1). In operation EVDs are installed in soil by a mandrel in similar patterns as PVDs (Fig. 2). A dc current is then applied across the EVD rows, which drives the soil pore water flow from anodes to cathodes, generates a negative pore pressure at the anodes and consolidates the soil.

The goal of this research is to study the electroosmotic process in soil using EVDs as both electrodes and drains. The study includes aspects such as voltage drops at the EVD-soil interface, the minimum applied current density that triggers water flows through soil, effect of polarity reversal, and EVDs' service life. Changes of soil properties before and after an electroosmotic treatment are also investigated, including the soil shear strength, compressibility, water content, electrical conductivity, porous water pH and other physico-chemical properties.

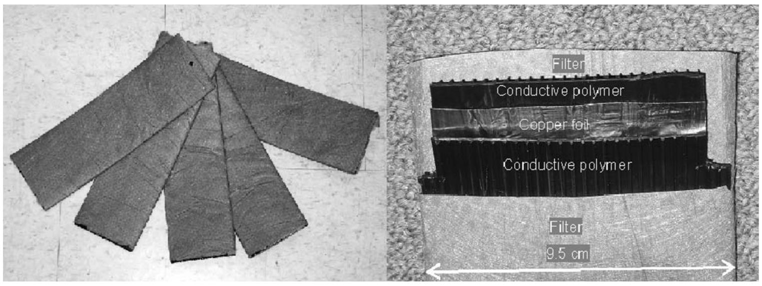

Fig. 1 Electrical vertical drains (EVDs)

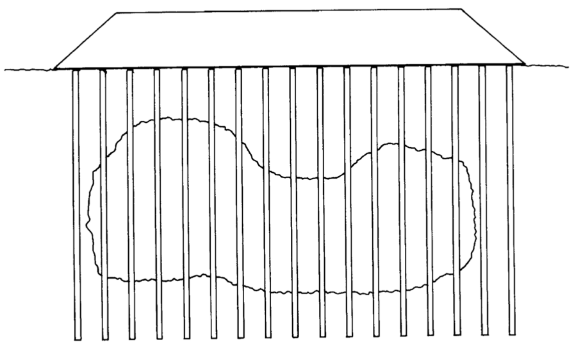

Fig. 2 Schematic of EVDs layout (US Patent 6,089,788, 2000)

2. Background

The commonly accepted theory of electroosmosis in soil is based on the Helmholtz-Smoluchowski model, which was originally introduced by Helmholtz in 1879, and refined by Smoluchowski in 1914 (Hausmann 1990). Based on the Helmholtz-Smoluchowski model, the water velocity generated by electroosmosis is expressed as (Mitchell and Soga 2006):

$$v_f = \left(\frac{\xi \cdot D}{\eta}\right) n \cdot E \tag{1}$$

where v_f is the water flow velocity in a porous medium such as soil; ξ is the zeta potential of solids; D is the relative permittivity of pore fluid; η is the viscosity of pore fluid; n is the porosity of pore fluid; and E is the electric field intensity, which is often referred as the voltage gradient in the literature.

The volumetric water flow rate in the soil can be expressed as:

$$q_A = \left(\frac{\xi \cdot D}{\eta}\right) n \cdot E \cdot A \tag{2}$$

where A is the cross sectional area normal to the flow direction.

By analogy with Darcy's law, Eq. (2) can be re-written as:

$$q_A = k_e \cdot E \cdot A \tag{3}$$

in which k_e is the coefficient of electroosmotic permeability. From Eq. (3), k_e yields theoretically

$$k_e = \frac{\xi \cdot D}{\eta} n \tag{4}$$

In practice, k_e is mostly commonly measured directly from experiments. A standard testing apparatus and procedure have been developed for the measurement of electroosmotic permeability of soil (Mohamedelhassan and Shang 2003).

Although Eq. (3) shows the water flow generated by electroosmosis is proportional to the electric field intensity (E), it has been demonstrated in experiments that the electrical current is the true driving force of the water flow in soil due to the nature of soil-water-electrolyte systems. By Ohm's law,

$$j = \kappa \cdot E \tag{5}$$

where j is the electric current density (A/m^2) and κ is the electrical conductivity ($S \cdot m^{-1}$). The water flow rate in Eq. (3) can be expressed as:

$$q_A = \frac{k_e}{\kappa} j \cdot A = \frac{k_e}{\kappa} I \tag{6}$$

where I is the electric current (A).

Eq. (6) shows that the water flow rate in an electroosmotic process is controlled by the electric current and soil electrical conductivity, both properties change with time in a soil-water-electrolyte system.

The electroosmotic process generates a negative pore pressure at a closed anode, which leads to consolidation. Esrig (1968) proposed a theoretical solution of electroosmosis consolidation based upon the development of pore water pressure under a uniform electrical potential field with no consideration of coupled electrochemical reactions. The maximum excess pore pressure, which takes place at the anode when cathode is drained and anode is sealed, can be expressed as:

$$u = \frac{k_e}{k_h} E \cdot \gamma_w \tag{7}$$

In the final steady-state condition ($t = \infty$) with anode and cathode sealed, the pore pressure is expressed as (Hausmann 1990):

$$u = 0.5 \frac{k_e}{k_h} E \cdot \gamma_w \tag{8}$$

where γ_w is the unit weight of water.

When electroosmosis is applied for soil consolidation, the excess pore pressure is negative at the anode and zero at the cathode. As a result, the shear strength gain due to consolidation is not linearly distributed from the anode to cathode. In addition the low pH and anodic oxidation at the anode cause corrosion of anodes made of consumable metals. To overcome these shortcomings, the technique of polarity reversal is often adopted in an electroosmotic treatment, i.e. the anode and cathode are switched periodically. The polarity reversal has the benefits of generating a more uniform soil shear strength gain, reducing the differential settlement, pH gradient and electrode corrosion (Shang *et al.* 1995, Hamir *et al.* 2001). In addition, the current intermittence, i.e. the dc current is applied intermittently during an electroosmotic treatment in soil, has been applied to enhance the efficiency of electroosmotic dewatering (Momamedelhassan and Shang 2003).

In an electroosmotic process, the electric current must reach a critical level to trigger the water flow in soil. The electric current applied to the soil depends on the applied voltage, type of electrodes and soil properties. Although much research has been conducted on electro-osmosis induced water transport in soil, the minimum electric current which induces a water flow in soil and the methodology to determine this minimum current has not been reported in the literature.

The effects of electrochemical reactions during an electroosmotic process in soil have been well documented. Among these reactions, the most significant process is the rapid development of pH gradient between anode and cathode. When an electric current is applied across a soil through electrodes, oxidation and reduction are taking place at the anode and cathode respectively;

At anode, $$H_2O - 2e^- \rightarrow 1/2O_2 + 2H^+ \tag{9}$$

At cathode, $$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{10}$$

The accumulation of H^+ ions at the anode leads to a pH drop of soil water to as low as 2, and the accumulation of OH^- ions at the cathode leads to the increase in the pH of soil water up to 12. As a result, the anode will corrode quickly if it is made of a consumable metal such as steel, copper or aluminum. Furthermore, the water pH influences the zeta potential of soil solids and leads to changes in the rate and direction of water flow in soil during electroosmotic processes (Vane *et al.* 1997, Mohamedelhassan and Shang 2003).

Because metal electrodes such as steel, copper, aluminum etc. corrode rapidly during an EO treatment, studies have been carried out to develop more effective electrodes. Electrokinetic geosynthetics (EKGs) and electrical vertical drains (EVDs) are examples of the effort, which combines drainage and electrical conduction functions. Studies on EKGs have been reported on stabilization of reinforced soil wall, dewatering of mine tailings, and separation of solids in sewage sludge (Chew *et al.* 2003, Glendinning *et al.* 2005, Glendinning *et al.* 2006). EVDs are mainly applied in soil improvement, with reported lab and field trials (Rittirong *et al.* 2008). However, the long term performance of these products needs further assessment.

3. Experiment

The schematic of the experimental apparatus is shown in Fig. 3. This system, modified from a system developed by Mohamedelhassan and Shang (2003), consists of an electroosmotic cell (EO cell hereafter), two vertical electrodes, a surcharge loading plate, an electrical circuit with a dc power supply, and two water reservoirs. The EO cell is made of 1.5 cm thick Perspex plates, 35 cm long, 10 cm wide, and 25 cm deep. The EVDs provided by the manufacturer (RasWILL Ltd.) were used as electrodes. As shown in Fig. 1, the EVD is made of conducting polymer with an entrapped copper foil. The geo-textile filter is designed to prevent the infiltration of soil solids into the drainage-conducting core. The dimensions of the EVDs are 95 mm wide and 6 mm thick. In the EO cell, the spacing between the anode and cathode EVDs is 18 cm. Two water reservoirs are used to control the water level in the EO cell. In order to generate one-dimensional horizontal flow across the EO cell, an impermeable geo-membrane is placed on the top of the soil specimen before placement of the loading plate. The soil settlements with elapsed time are monitored by two dial gauges mounted on the loading plate. Five voltage probes are installed into the soil specimen at an equal spacing of 3 cm to measure the voltage distribution in the soil.

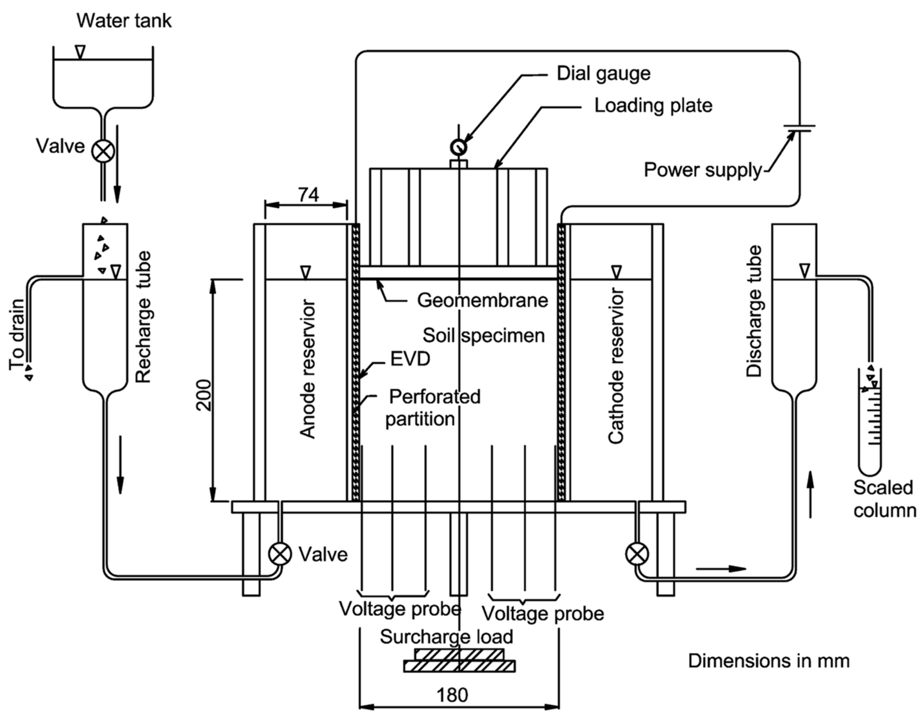

Fig. 3 Electroosmotic cell setup

Table 1 Summary of soil properties

Water content (%)	120
Liquid limit (%)	60
Plastic limit (%)	40
Plasticity index	20
Specific gravity, Gs	2.46
Undrained shear strength (kPa)	4-5
Electrical conductivity (S/m)	0.15
pH of pore water	7.8

In the tests, the hydraulic gradient was set to zero, i.e. the water tables in the both reservoirs were kept at the same level by adjusting the heights of recharge and discharge tubes connected to the reservoirs. When a dc voltage was applied, the water was supplied by the anode reservoir, flowing through the soil in the EO cell from the anode to cathode, entering the cathode reservoir and discharging to the graded cylinder for real time measurement. During this process, the water levels in both reservoirs were kept constant.

A constant voltage was applied across the EO cell via EVDs using a dc power supply with a capacity of 25 V and 2.0 A. The polarity of the current was reversed every 24 hours. The electric current was monitored by an ammeter while the applied voltage was kept constant.

The tests were conducted on a marine clay recovered from the southeast coast of the Korean Peninsula at the Yulchon land reclamation site. The soil physical properties are summarized in Table 1.

It has been well established from the theoretical aspects and experimental observations that electroosmosis diminishes when the salinity of soil pore water exceeds a certain level. In order to reduce the soil salinity, the soil was placed in a plastic barrel and mixed with tap water. Then the top water was decanted and the soil was placed in a metal tray to air dry until the soil moisture content reduced to approximately 80% and formed a consistency that could be easily placed into two identical electroosmosis cells, one for the EO testing and another as a control test without EO treatment. Before deposition into the electroosmosis cells the soil was mixed by a blender to ensure uniform moisture content.

After the soil was placed into the EO cells, it was consolidated to a pre-determined density. An incremental preloading pressure of 4.75 kPa was added every 24 hours until the final preloading pressure reached 19.2 kPa. The excessive pore water in the soil was allowed to dissipate through EVDs. The electroosmotic testing was carried out on one EO cell when the preloading consolidation came to a full stop. The soil specimen after the preloading consolidation had the dimensions of 10 cm wide, 18 cm long and 15.4 cm high. The soil was fully saturated, had an average water content of 56%, void ratio of 1.4 and dry density of 10.4 kN/m^3. The initial vane shear strength was approximately 5 kPa.

The experimental program was designed to assess the performance of EVDs and changes of soil properties by electroosmotic treatment. The applied voltage in the electroosmosis test was 25 V across the soil specimen length, which generated a constant applied voltage gradient of 133 V/m. The electric current was 0.2 A on a soil cross-section of 10 cm×15.4 cm at the beginning of the test, which corresponded to a current density of 13 A/m^2. The test duration was 19 days, but the water flow stopped completely after 16 days. After the test, the vane shear strength, moisture content, Atterberg limits and zeta potential of the soil were measured.

4. Results and discussion

4.1 Voltage loss, efficiency and service life of EVDs

In the EO cell test the polarity of the applied voltage was reversed every 24 hours. For the ease of discussion, the normal polarity (NP) is referred as the EVDs on the left side of the EO cell functioning as the anode and the EVDs on the right side of the EO cell as the cathode, as shown in Fig. 1. Under the NP mode, the applied voltage and corresponding current are expressed as positive. The left EVD anode and right EVD cathode is referred as the reversed polarity (RP). Under the RP mode, the applied voltage and current are expressed as negative. Under a constant applied voltage gradient of E_o=133 V/m (25 V over the EVD spacing of 18.8 cm), the voltage gradients in the soil specimen during the normal and reversed polarities are presented in Fig. 4. The difference between the applied voltage gradient and effective voltage gradient is clearly shown in the figure. Due to the voltage drops on the cathode and anode, the effective voltage gradients in the soil were reduced to less than 90 V/m under the normal polarity and to as low as 20 V/m under the reversed polarity. The efficiency of the EVDs for power transfer, defined as the ratio of the effective voltage gradient and the applied voltage gradient, E_{eff}/E_o, is presented in Fig. 5. Under the normal polarity, the efficiency is typically 70% or lower, which is consistent with the results on carbon-carbon electrodes reported in previous study (Mohamedelhassan and Shang 2003). Under the reversed polarity, however, the efficiency was only about 30% at the beginning and reduced to only 10% after 6 days. It was further found that the EVDs lost the ability to conduct current after 15 days.

To further assess the property change of the EVD electrodes, the EO cell was filled with tap water and the EVDs used in the EO cell test were reinstalled. The voltage drops between the EVD and water interface were measured, as shown in Fig. 6. It was found that the EVD on the right side of the EO cell has completely lost its ability to conduct current, with a voltage loss up to 20 V under an applied voltage of 25 V. On the other hand, the EVD on the left side of the cell remained mostly intact, with a voltage loss of 2.5 V at an applied voltage of 25 V. The loss of conductance for EVD has also been reported in another study (Rittirong *et al.* 2008). In that case, the polarity reversal was not applied and the voltage drop on the EVD anode was up to 50% after 11 days.

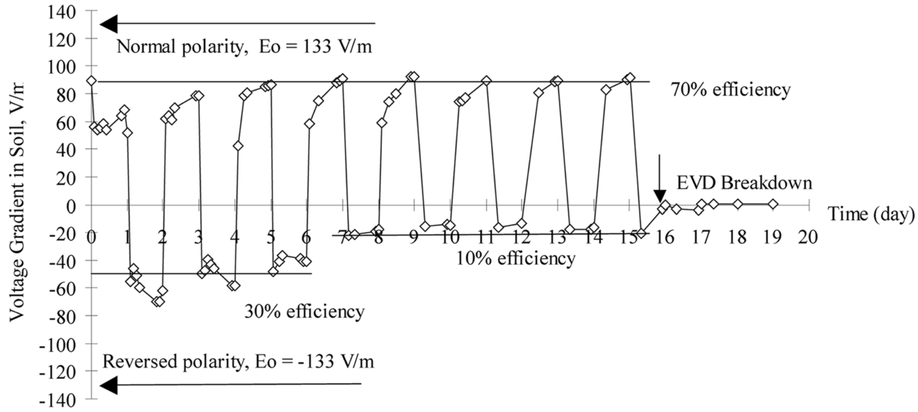

Fig. 4 Voltage gradients in the soil specimen during the normal and reversed polarities

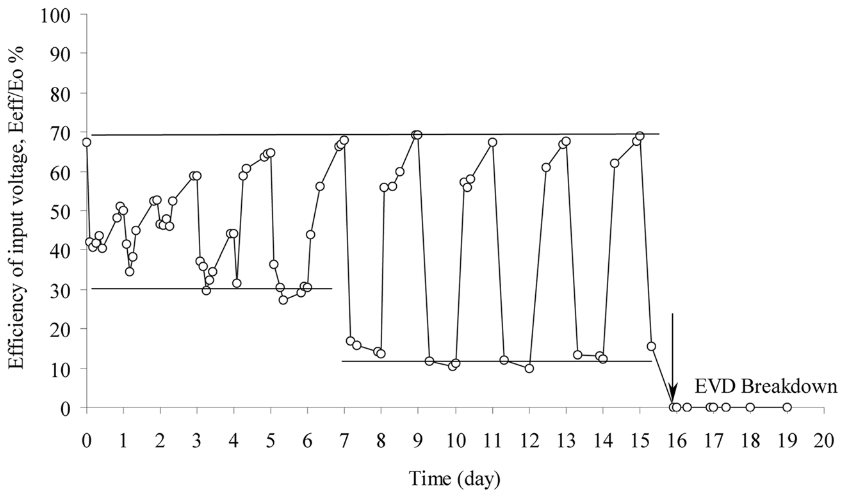

Fig. 5 Efficiency of input voltage, E_{eff}/E_o versus time

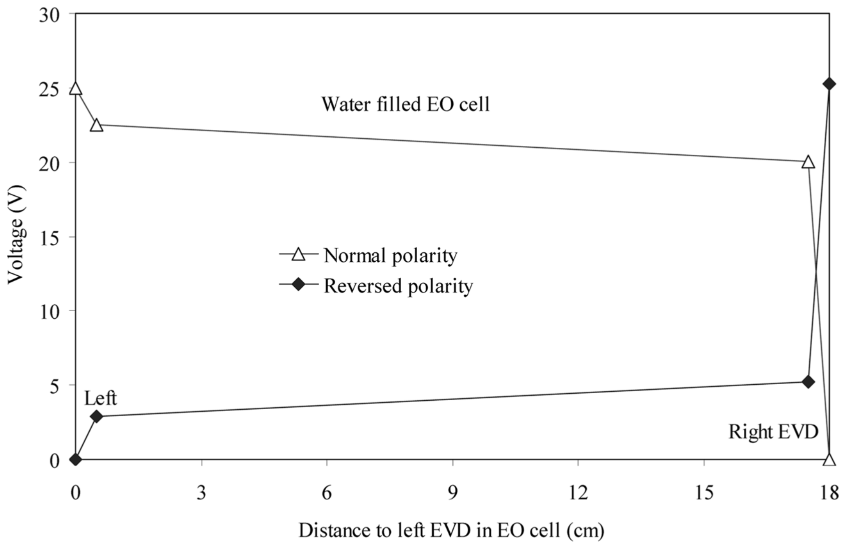

Fig. 6 Voltage drops in the electroosmotic cell

4.2 Electrical current and electroosmotic water flow

The electrical current was normalized against the cross-sectional area of the EO cell and presented as the current density. The results versus time during the EO cell test are presented in Fig. 7. It is shown that the current density under both normal and reversed polarities reduced gradually until the EVD breakdown after 15 days. The current density under reversed polarity, however, was at a much lower level throughout the test. This indicates that the EVD on the right side of the EO cell, when used as the cathode under the normal polarity, has been damaged in the first day of the EO cell test, as evidenced in Fig. 6. The significantly reduced current with EKGs as electrodes was also observed by other researchers (Karunaratne *et al.* 2004).

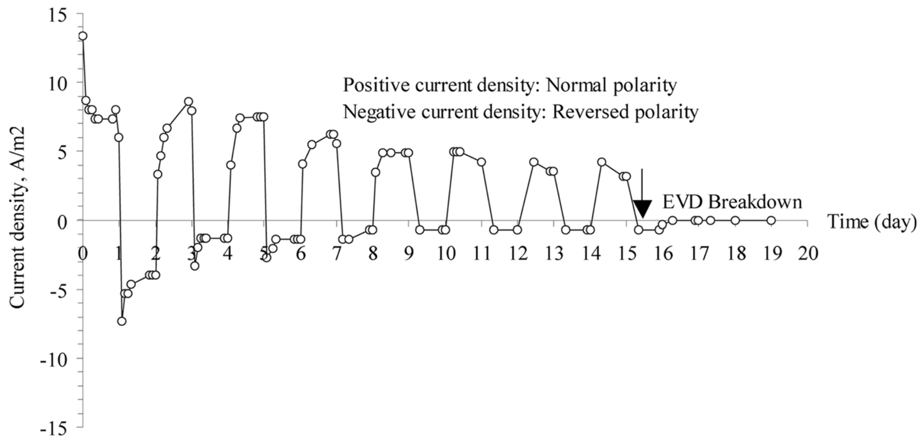

Fig. 7 Current density versus time

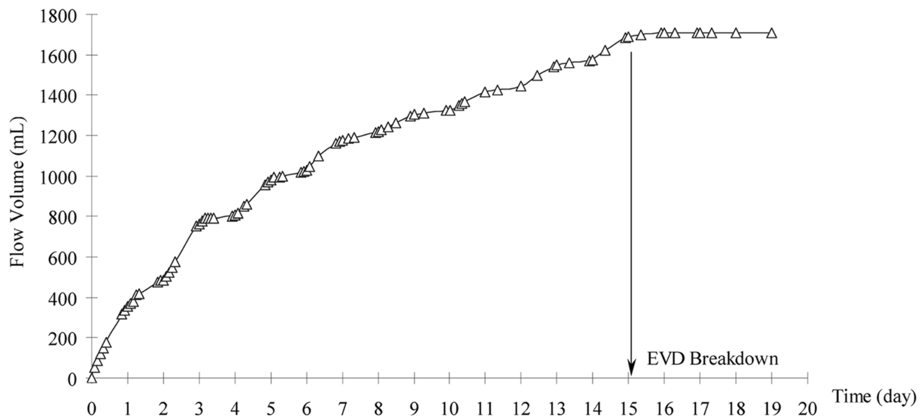

Fig. 8 Accumulated volume of water flow during the EO cell test

Fig. 8 shows the accumulated volume of water flow during the EO cell test. Since the hydraulic gradient on the EO cell was set to zero, the water flow was generated solely by electroosmosis. The total water flow over 15 days was 1700 mL. Since the pore volume of the soil specimen was known as 1754 cm^3, the result showed that 97% of the soil pore water has been replaced during the EO cell test. It should be noted in the EO cell test, the water was driven to the right side of the EO cell during the normal polarity and to the left side of the EO cell during the reversed polarity.

The water flow rate during the EO cell test is presented in Fig. 9. The trend is similar to that of the current density (Fig. 7), indicating the effective voltage gradient and corresponding current density in soil are indeed the driving force for water transport by electroosmosis. The flow rate during the normal polarity mode varied between 20 mL/hour and 6 mL/hour, and was much lower during the reversed polarity mode at between 4 mL/hour and 1 mL/hour, obviously attributed to the lower current density under the reversed polarity mode.

The current density versus water flow rate during the EO cell test is presented in Fig. 10. It is shown that the flow rate directly calculated from the accumulated water flow (Fig. 9) varied in a rather large range, which may be attributed to errors in measurement as well as the flow disruption due to polarity reversal. The general trend of the flow rate increase with the current density,

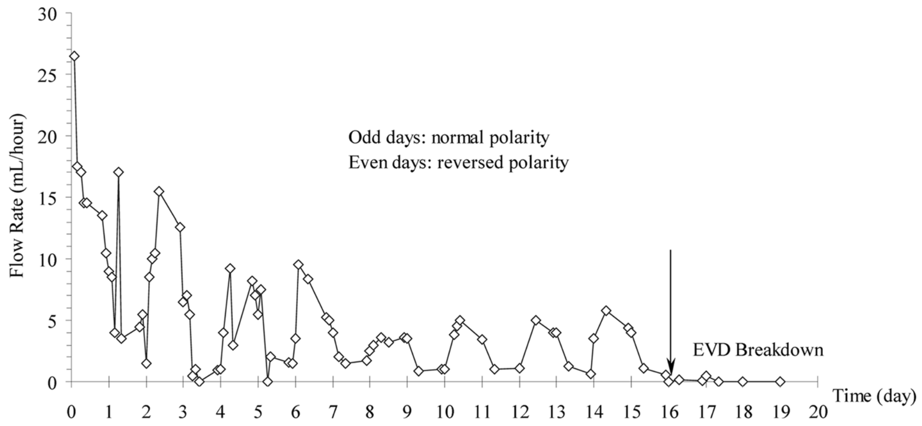

Fig. 9 Water flow rate versus time during the EO cell test

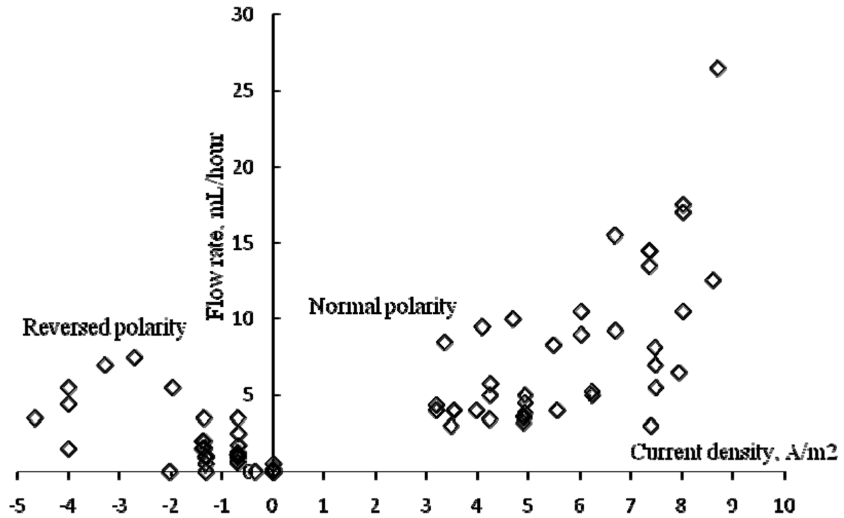

Fig. 10 Current density versus water flow rate during the EO cell test

however, is quite clear.

4.3 Electroosmotic permeability

The electroosmotic permeability, as defined in Eq. (3), is thought to be an intrinsic property of soil and often cited as a constant for a specific soil in the design of electroosmotic treatment (Mitchell and Soga 2006). In reality, however, it has been evidenced by many researchers that k_e varies with time during an electroosmotic process (Mohamedelhassan and Shang 2003). The k_e measured in the EO cell test in this study is presented in Fig. 11. The results show that k_e is largely independent of the electrode's polarity and is a function of time. The results also suggest that k_e values approached a constant value after approximately 3 days of testing until the EVD breakdown after 15 days. In the development of a numerical model for EO consolidation, therefore, the time dependent k_e values should be incorporated. For design purposes, a constant k_e value obtained after 3 days of EO cell testing may be selected.

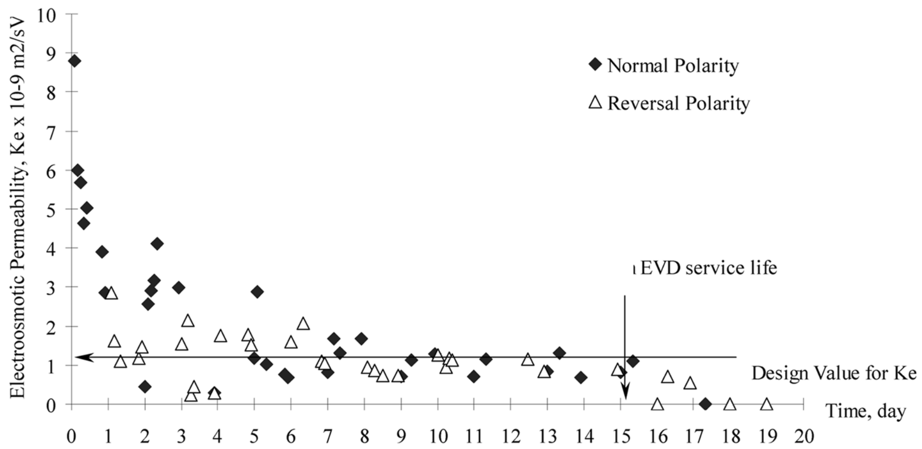

Fig. 11 Electroosmotic permeability, k_e, versus time

4.4 Soil properties

Fig. 12 shows the distribution of vane shear strength across the soil specimen in the EO cell after 19 days. The vane shear strengths were measured in 30 mm depth at three locations across the EO cell. The vane shear strength of the soil after the control test (without EO treatment) was about 4 kPa and about 23 kPa after the EO cell test. The results are similar to those reported by Lo *et al.* (1991). The distribution of soil moisture content after the electroosmotic treatment is shown in Fig. 13. The soil water content was measured at six locations across the EO test cell and control test cell at 65 mm depth. The soil water contents in the control cell had lower values at EVD drains on both ends and remained constant in the mid-section. In the EO cell, however, the trend was opposite. The soil water contents were higher at both ends and lower in the mid-section of the soil specimen. In particular, the soil water content at the centre reduced to 40% from the original 56%. This was

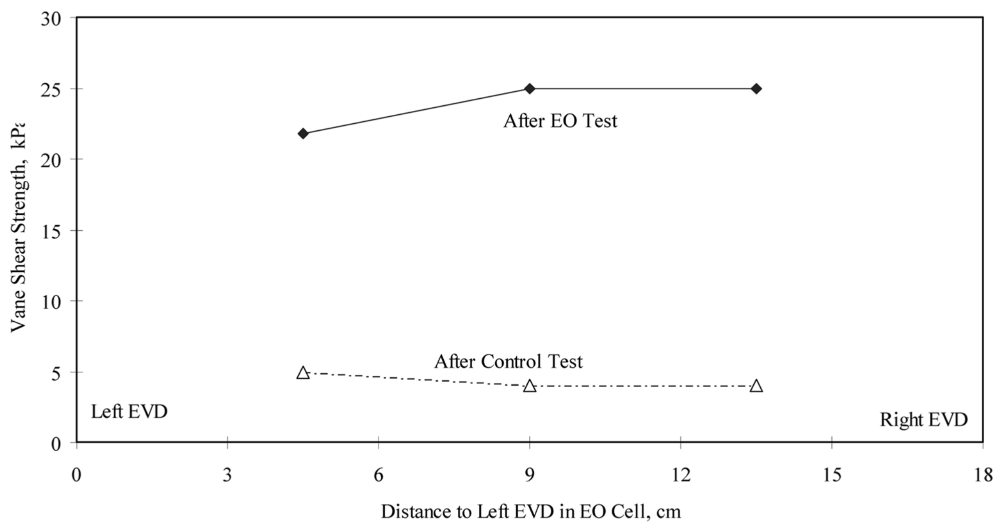

Fig. 12 Distribution of vane shear strength across the soil specimen in the EO cell after 19 days

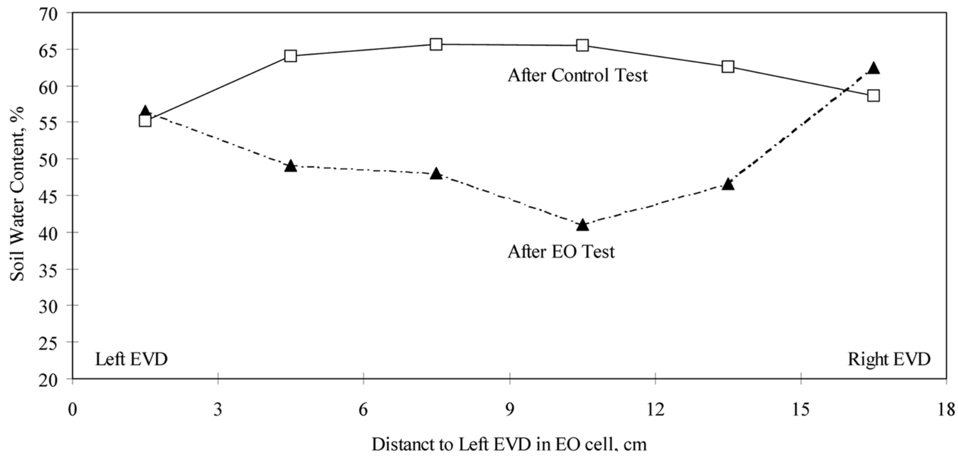

Fig. 13 Distribution of soil moisture content after the electroosmotic treatment

obviously attributed to the electroosmotic water transport and polarity reversal during the EO cell test. Electroosmosis generated water flow toward both sides of the EO cell during NP and RP modes, which resulted in the reduction of soil water contents in the middle section. It is of interest to note that although the soil moisture contents adjacent to both electrodes did not change significantly after the electroosmotic treatment, the vane shear strength increased up to four folds (Fig. 12). The results demonstrated an important benefit of the electroosmotic treatment in addition to consolidation, namely, generating cementation and strength gain from electrochemical reactions, which has been reported extensively in the literature.

Fig. 14 presents the soil Atterberg limits measured before and after the EO cell test. The results are not sufficiently clear to indicate any significant changes as reported in many other studies (Micic *et al.* 2001, 2002, Rittirong *et al.* 2008). Although further study is needed, this is likely attributed to the polarity reversal, which reversed electrochemical reactions at the anode and cathode.

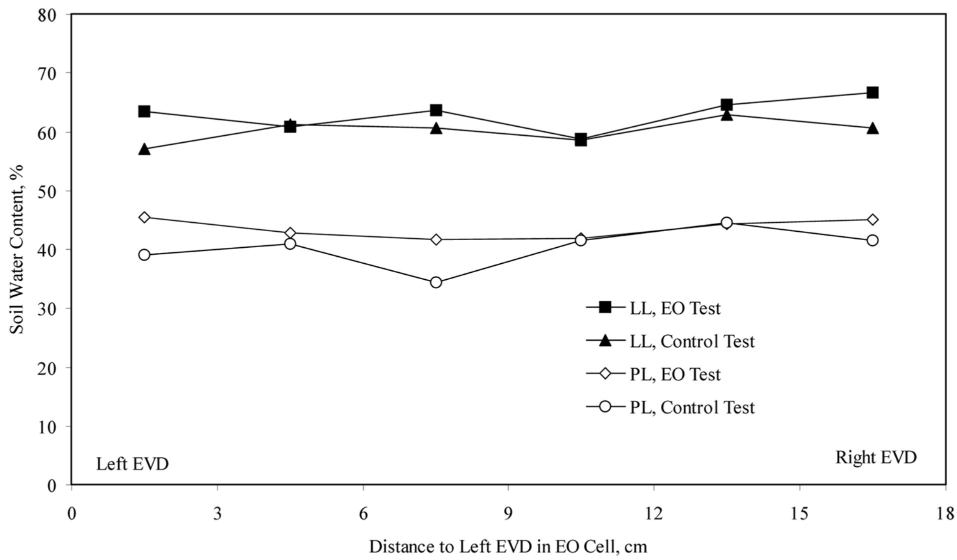

Fig. 14 Soil Atterberg limits measured before and after the EO cell test

Fig. 15 presents the consolidation curves of the Yulchon clay before and after the electroosmotic treatment. The soil specimen for the consolidation test was trimmed from the soil specimen at the centre of the EO cell, with a moisture content of 40% and void ratio of 1.1. The pre-consolidation pressure after the EO treatment increased more than 400%. The result also indicated that the coefficient of volume compressibility, C_c, decreased from 0.5 to 0.27, and the Coefficient of consolidation, C_r, decreased from 0.4 to 0.35.

Fig. 16 presents the soil pore water pH distribution after the EO cell and control tests. The soil pore water was squeezed from the soil sample under 1 MPa using a pore fluid squeezer. The pore water pH of the soil after the EO test was between 5.6 and 9.5. It is of particular interest to compare the pH values of the soil pore water and two reservoirs on the EO cell, as shown in Fig.

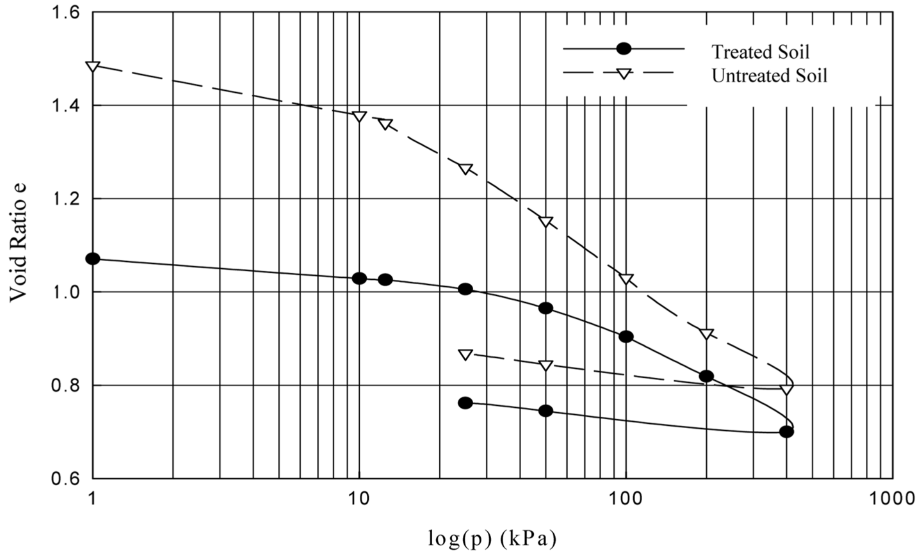

Fig. 15 Consolidation curves of the Yulchon clay before and after electroosmotic treatment

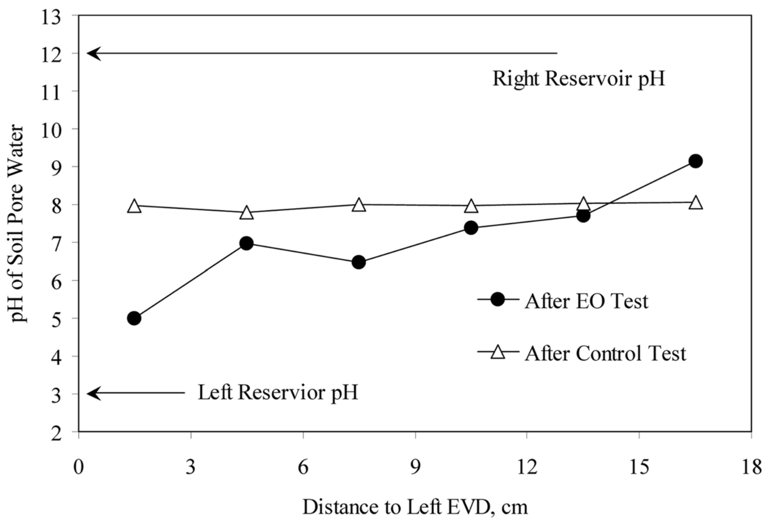

Fig. 16 Soil pore water pH distribution after the EO cell and control tests

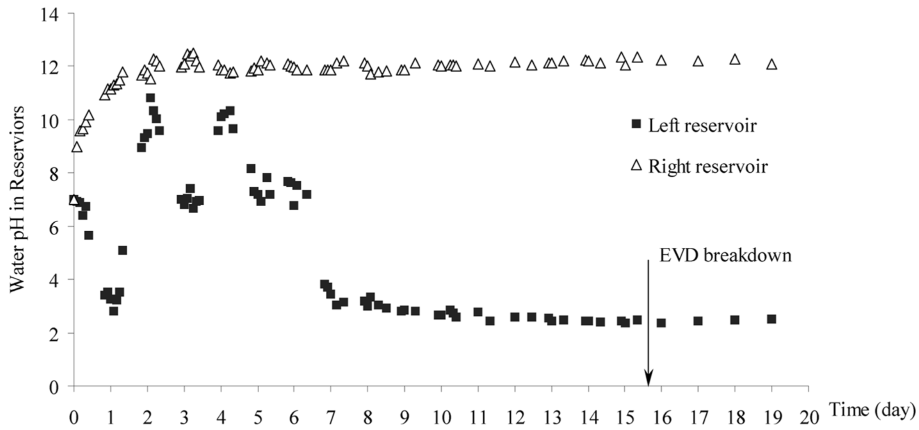

Fig. 17 Water pH in anode and cathode reservoirs

16. The pH values on the left and right reservoirs after 19 days of EO test were pH 3 and pH 12, respectively. However, the soil pore water pH remained relatively neutral in spite of the fact that the soil was in direct contact with the water in the reservoirs.

The reservoirs pH values versus time during the EO test are presented in Fig. 17. It is shown that polarity reversal affected the reservoir pH only during the first six days of the EO test. The left and right reservoirs remained at constant pH 3 and pH 12 after day 6, respectively, and were no longer responding to polarity reversal.

5. Conclusions

The electroosmotic process generated by electrical vertical drains (EVDs) is studied on a marine clay in an experimental program. The results of the study show that the EVDs can effectively induce the water flow, consolidation and strength gain in the soil. After 19 days of EO treatment under a constant applied dc voltage gradient of 133 V/m, the soil's moisture content decreased by 28%, the shear strength and pre-consolidation pressure increased more than 400%. The dc current density required to trigger water flow in the marine clay tested is 0.7 A/m^2. The project demonstrates that EVDs can serve as both electrodes and vertical drains in short term. The electrical current conduction efficiency of the EVDs was in the range of 70% over a period of 15 days without polarity reversal. However, the EVD as tested is not suitable for polarity reversal and its service life is limited to only 15 days under the applied voltage gradient of 133 V/m that is of typical in soil improvement applications.

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