

Study on the applicability of electro-osmotic consolidation to on-site ground improvement

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ABSTRACT: Electro-osmosis (EO) has been investigated as an on-site consolidation method for soft clay for a long time. Although the use of electroosmosis in geotechnical and geo-environmental engineering has extensive application potential, such as soil consolidation and stabilization, strength improvements, soil remediation, and dewatering of sludge, an efficient method to enhance the EO effect while minimizing energy consumption is still being explored. Conventional EO consolidation employs a pair of electrodes, one serving as the anode and the other as the cathode, to induce the movement of pore water through soil by applying an electric field. When using conventional electrodes, the potential gradient in clay depends on the electrode spacing. Therefore, achieving a high EO effect with increased electrode spacing requires considerable energy, making it difficult to apply the EO consolidation as an on-site ground improvement method. To address this issue, this paper investigates an efficient method to achieve a high EO effect with low energy consumption. To this end, laboratory tank tests were conducted with various electrode spacings using a newly developed electrode, the \pm integration (\pm int.) electrode. The experimental results showed that a high EO effect with low energy consumption was achieved using the \pm int. electrode, even with increased electrode spacing. This is because the EO effect with the \pm int. electrode is not affected by electrode spacing, as it contains both an anode and a cathode within the same electrode. The results using a single \pm int. electrode indicated that the influenced area was approximately 0.5 m. Additionally, EO consolidation can occur more uniformly if overburden pressure is applied on top of the ground. These findings could be applied to future electrokinetic treatment techniques, including the development of advanced electrodes such as electrokinetic geosynthetics, and contribute to more efficient construction practices.

KEYWORDS: Electroosmosis, Consolidation, Clay, Ground improvement.

1 INTRODUCTION

Electro-osmotic (EO) technology is an effective method for slurry consolidation, and the electric potential distribution and electrode spacing have a large effect on EO consolidation. Normally, two electrodes, one an anode and the other a cathode, are needed to apply electric current. In this study, a pair of these electrodes is called conventional (conv.) electrode. EO refers to the movement of pore water through soil induced by an applied electric field. Although this results in the rapid consolidation of clayey ground, the potential gradient in clay depends on the electrode spacing when conv. electrodes are used. Although many field tests have been conducted using electrokinetic treatment (e.g. Chew et al., 2004; Mahmoud et al., 2010), achieving a high EO effect with increased electrode spacing requires considerable energy, making it difficult to apply the EO consolidation as an on-site ground improvement method.

To address this issue, various electrode materials have been developed (Jones and Lamond, 2011; Karunaratne, 2011; Liang and Changhong, 2020). Additionally, Tao et al. (2022) investigated different electrode arrangements, and Sugiyama et al. (2024) developed new electrodes to control the potential distribution in clay. However, the efficient method to enhance the EO effect while minimizing energy consumption is still being explored.

This paper investigates the efficient method to achieve a high EO effect with low energy consumption. To this end, laboratory tank tests were conducted with newly developed electrode to control the potential distribution in clay. The influence of electrode spacing was investigated by performing tests at various spacings between the electrodes.

2 MATERIALS AND METHODOLOGY

2.1 Materials

In this study, kaolin clay was used as the ground material. The physical parameters are shown in Table 1. For the electrode material, iron was chosen as the electrode material with low voltage loss at the clay/electrode interface based on the results of the polarization tests reported by Sugiyama et al. (2024). The electrode is perforated with multiple small holes, with the total area of these holes comprising 20% of the electrode's surface, allowing for efficient drainage of pore water.

Table 1. Physical properties of kaolin clay

Soil particle density (g/cm^3)	2.77
Wet unit weight (g/cm^3)	1.47
Liquid limit (%)	52.1
Plasticity index	22.4
Permeability (cm/sec)	6.3E-06

The \pm integration (\pm int.) electrode was newly developed to control the potential distribution in the soil. The schematic images of both conv. and \pm int. electrodes are shown in Figure 1. The \pm int. electrode is divided into several blocks by insulator of 2 mm thickness. This electrode has both an anode and a cathode within the same electrode. Anode potential and cathode potential of 0 V are applied to each block alternately. The initial potential distribution for both conv. and \pm int. electrodes are shown in Figure 2. The potential distribution was calculated using Laplace's equation, induced by the Ampere-Maxwell law and Faraday's electromagnetic induction law.

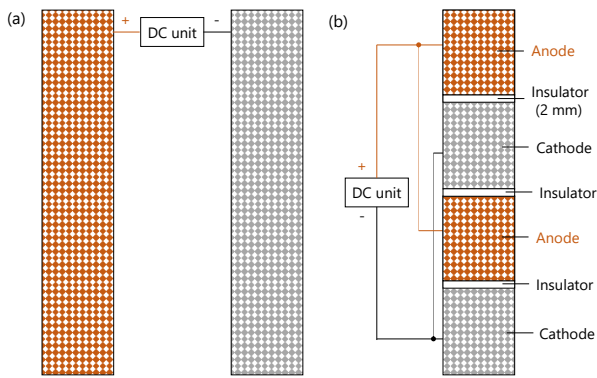


Figure 1. Schematic images: (a) conv., and (b) \pm int. electrode.

In the case of conv. electrode, the potential between the electrodes increases from 0 V at the cathode to a higher value at the anode, and the electric current flows perpendicular to the equipotential lines, as shown in Figure 2a. The electrode spacing was 0.1 m, the height of the ground was 0.1 m, and the anode potential was set to 70 V. EO flow occurs due to potential differences, causing the pore water flows from anode (high potential area) to cathode (low potential area). When the \pm int. electrode is used, the current flows from the anode of the upper block to the cathode of the bottom block on both sides, as shown in Figure 2b.

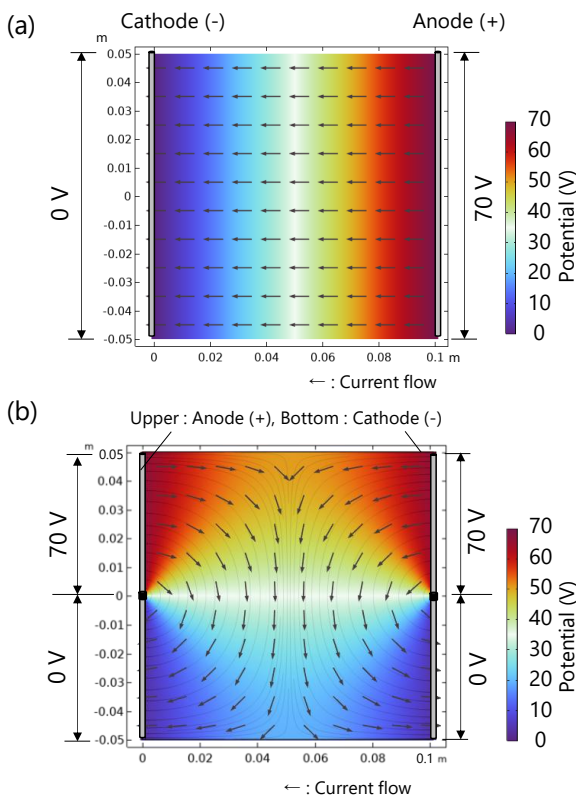


Figure 2. Initial potential distribution and current flow in clay: (a) conv., and (b) \pm int. electrode.

2.2 Experimental setup and test methodology

Figure 3 presents the schematic diagram of the test model setup. The tests were conducted in a 1.1 m (length), 0.05 m (wide), and 0.2 m (deep) tank. The setup facilitates the electrodes to be placed at varying spacings, ranging from 0.1 m to 1.0 m in 0.1

m increments, enabling testing under different electrode spacing conditions. A drain was attached to the electrode to allow pore water drainage, and the dewatering volume was measured on both sides. In all tests, the cathode (or \pm int. electrode) was placed 0.05 m from the left end of model tank, and the anode (or \pm int. electrode) was placed at distances of 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, and 1.05 m from the cathode. Additionally, a camera was positioned on the side of the model tank to capture ground deformation through images.

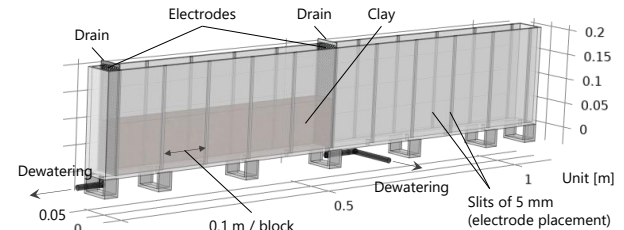


Figure 3. Layout of the laboratory test

The clay sample was prepared mixing powdered kaolin clay with tap water in a mixer at water content of 100 %, which is approximately twice the liquid limit. A surface texture contrasting with the white color of the clay was created by coating the sides of the model tank with colored kaolin for image-based measurements. Then, the clay slurry was filled into the tank to a height of 0.1 m between the electrodes. The \pm int. electrode can direct the current flow using a single electrode because both the anode and the cathode are integrated within the same electrode. However, the electrodes are placed in a grid pattern on-site. Therefore, in this study, the \pm int. electrodes are installed on both sides of the model tank.

Additionally, to investigate the area influenced by EO when using a single \pm int. electrode, a laboratory test was conducted in which a single \pm int. electrode was placed at 0.05 m, a partition plate was placed at 1.05 m, and the tank (1.0 m wide) was filled with kaolin. A current density of 1.2 mA/cm² was initially applied to the clay under constant current conditions in all tests to initiate EO dewatering. All tests were conducted for a duration of 24 hours across the different electrode spacings to evaluate the EOD effect. For the 1.0 m electrode spacing, the test was extended beyond 24 hours to further examine the dewatering process until the discharge volume became negligible, thereby providing additional insights into the long-term behaviour.

3 RESULTS AND DISCUSSIONS

3.1 Electroosmotic dewatering

Figure 4 shows the normalized dewatering over time at different electrode spacings. The normalized dewatering was calculated by dividing the dewatering volume by the electrode spacing to account for the influence of spacing on dewatering efficiency and enable a direct comparison across different setups. The dewatering discharge, represented by the gradient of the normalized dewatering curve over time, exhibited a reduction with increasing electrode spacing across all electrode configurations. However, sufficient normalized dewatering over 24 hours was obtained with the electrode spacing ranged from 0.1 to 0.6 m. The dewatering discharge with an electrode spacing of 1.0 m continued to increase after 24 hours, indicating that the sufficient dewatering can be achieved with a longer duration of electric current application.

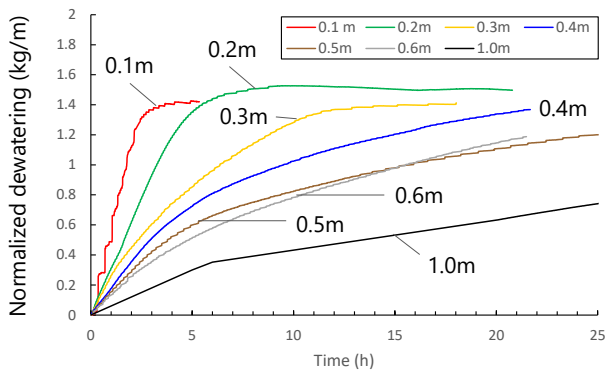


Figure 4. Change in normalized dewatering over time.

3.2 Single \pm int. electrode

Figure 5 shows the change in normalized dewatering using single and two \pm int. electrodes in a 1.0 m-wide soil tank. The initial dewatering discharge exhibited a similar trend for both setups. However, the normalized dewatering gradually decreased over time. After 24 hours, the normalized dewatering with a single \pm int. electrode was half of that observed with two \pm int. electrodes, suggesting that the influenced area with a single \pm int. electrode was approximately 0.5 m.

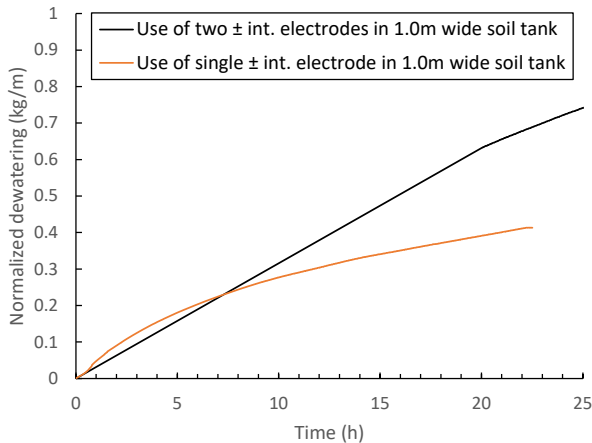


Figure 5. Comparing the results using single or two \pm int. electrodes.

3.3 Degree of dewatering and energy consumption

The degree of dewatering, calculated as the ratio of the dewatering volume over 24 hours to the initial pore water volume, is shown in Figure 6a. In this figure, red plots represent the final dewatering rate achieved with a 1.0 m electrode spacing. The energy consumption required to remove 1.0 g of pore water in 1.0 hour, as shown in Figure 6b. The x-axis in both figures represent the electrode spacing. For comparison with the EO effect, Figure 6 also includes results obtained using conventional electrodes.

As the electrode spacing increased, the degree of dewatering significantly decreased with the conv. electrode. In contrast, the degree of dewatering with the \pm int. electrode remained between 30% and 40% across all electrode spacings except for the 1.0 m electrode spacing, indicating that the EO effect remained consistent regardless of the electrode spacing. The final dewatering rate with 1.0 m using \pm int. electrode was 39%, suggesting that a high EO effect could be achieved if the electric current was applied until dewatering was complete.

The energy consumption with the conv. electrode ranged from 0.002 to 0.006 Wh/dry gram, except in the case of 0.1 m electrode spacing. For the \pm int. electrode, the energy

consumption gradually decreased as electrode spacing increased. Comparing the results of degree of dewatering and energy consumption highlights the importance of selecting the optimal electrode type with low energy consumption to achieve a high EO effect. The conv. electrode is more suitable for 0.2 and 0.3 m electrode spacing, and the \pm int. electrode is the best choice for achieving a high EO effect when the electrode spacing exceeds 0.3 m.

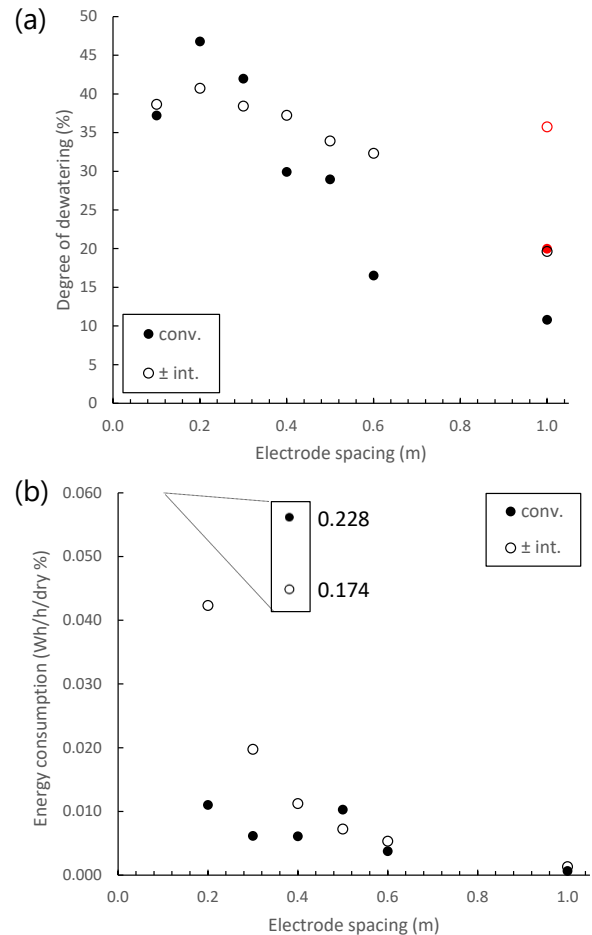


Figure 6. The results: (a) degree of dewatering, and (b) energy consumption required to dehydrate 1.0 g.

3.4 Influence of overburden pressure on EO effect

To investigate the EO dewatering effect on-site, an overburden pressure of 1.12 kPa was applied on top of the ground using lead balls on a stiff, electrically insulating board during the test with the \pm integration electrode. The electrode spacing was 0.6 m, and the electrical conditions remained as previously described.

Figure 7 shows the change in dewatering volume and electric resistance versus time. The dewatering curve showed a similar tendency in both cases. However, the electric resistance with loading was smaller than that without loading, as this prevents the clay from peeling off the electrodes. Comparing these results shows that the EO effect become higher with loading. Figure 8 shows the settlement over time measured at 0.1, 0.3 and 0.5 m, including the results without loading. Comparing the cases with and without loading indicates that the EOC can be occurred more uniformly if overburden pressure is applied.

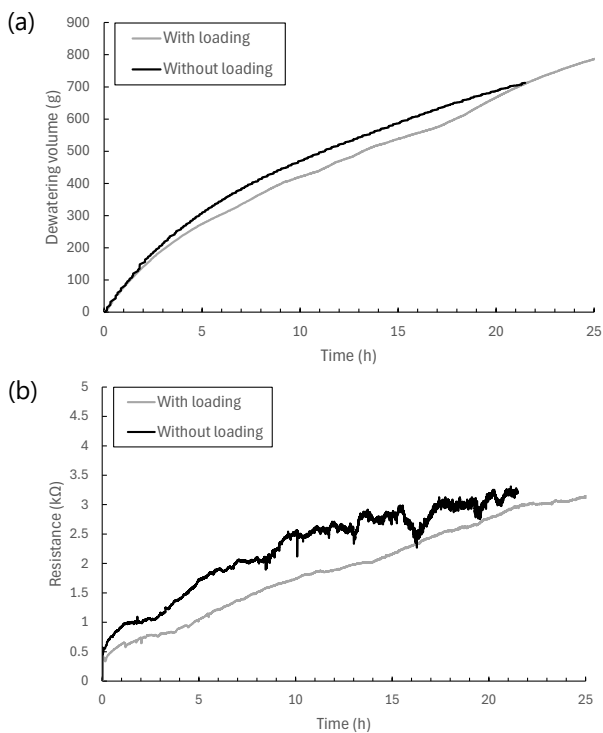


Figure 7. Comparing the results with and without loading: (a) dewatering volume, and (b) electric resistance versus time.

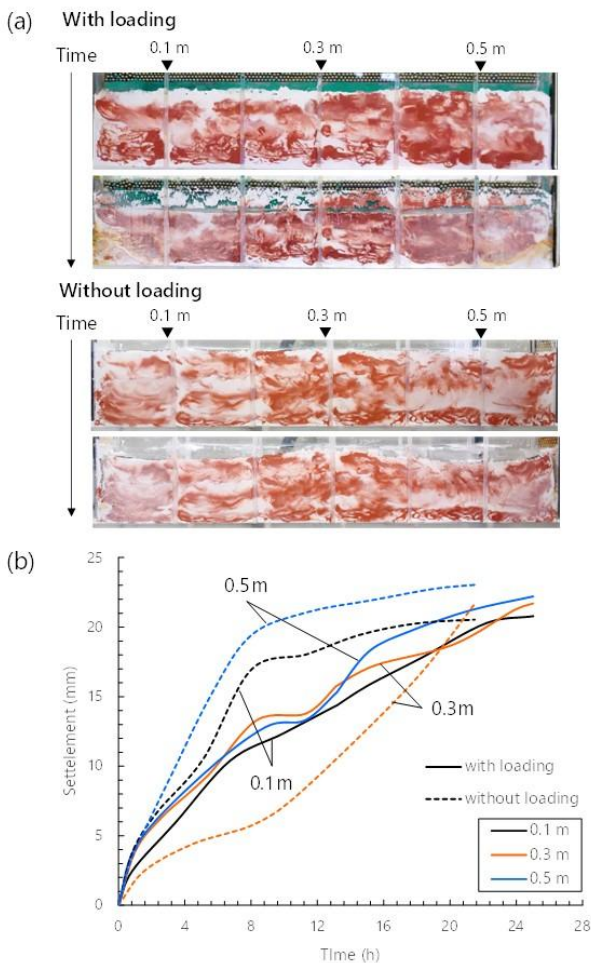


Figure 8. Comparing the settlement over time with and without loading.

4 CONCLUSIONS

The laboratory tank tests were conducted with various electrode spacings using electrodes that were developed to control the potential in clay. A high EO effect with low energy consumption was achieved by using \pm int. electrode even with increased electrode spacing. The results using a single \pm int. electrode indicated that the influenced area was approximately 0.5 m. Additionally, the EO consolidation can occur more uniformly if overburden pressure is applied on top of the ground. This finding could be applied in future electrokinetic treatment techniques including a developing electrode such as electrokinetic geosynthetics, and contribute to more efficient construction practices.

5 REFERENCES

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