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Investigation of Soil Consolidation for The Combined Technique of Electro-osmosis and Preloading

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ABSTRACT:
Discovered in the 19th century, electrokinetic phenomena has been researched extensively over the past few years. Recently, need for additional land within large cities has led to the reclamation of areas once deemed undesirable and filled with sludge. This has increased the desire to understand the process of electro-osmosis as a method of ground improvement in coastal areas undergoing rapid expansion.

Electro-osmosis has several advantages over other methods of ground improvement, some of these include; reduced equipment on the construction site, lack of reliance on particle size of soils, permanent effects etc… However, while electro-osmosis possesses several advantages, it continues to lag in use due to a lack of proper standardised testing as well as large discrepancies between analytical solutions and in-situ results.

To enhance the effects and efficiency of electro-osmosis, while lowering electrode corrosion, surcharge was added to electro-kinetic process for one-dimensional, two-dimensional and hexagonal one-dimensional electrode arrangements. Furthermore, a self-made box (60cm*45cm*45cm) with cathode electrodes made of synthetic plastic wrapped with steel wire was incorporated. An spd-3606 DC power supply was used to apply 25V to the soil sample. The desired water content percentage of each experiment was roughly 70%, and total experiment time was 72 hours. The cumulative discharge, drainage rate, water content (upper and subsoil layers), deformation and cracks were observed.

The data presented in this study focusses on better understanding the mechanisms contributing to the consolidation and deformation (vertical and horizontal) of soft soil under the combined method of electro-osmosis only and electro-osmosis with loads. It was observed that largest discharge volume of expelled water (40546.59 ml) occurred during electro-osmosis combined with surcharge coupled with two-dimensional electrode arrangement. The lowest cumulative discharge (11856.42 ml) was observed under the hexagonal one-dimensional electrode arrangement with electro-osmosis only. Furthermore, 2682.64 ml/h was the highest calculated drainage rate which occurred in experiment M2 (electro-osmosis combined with surcharge for two-dimensional electrode arrangement) after 20 hours of experiment time. While the water content readings were all lower than the initial percentage, the electro-osmotic phenomena resulted in an uneven distribution of water content percentage within the soil mass. Additionally, largest average vertical deformation within the soil mass occurred in one-dimensional electrode setup combined with surcharge (46.58mm). Each electrode arrangement yielded different crack patterns and sizes. However, compared to electro-osmosis only, reduction in cracks was evident under each of the combined method experiments.

It is concluded that Improvement in electro-osmotic efficiency with regards to drainage rate, cumulate drainage, water content and deformation was observed in the combined method of electro-osmosis with loads. Furthermore, the electro-osmotic improvement did not solely depend on the loads, but also depends on electrode arrangement.

Key Words: Electro-osmosis, combined method, electrodes, drainage, deformation.

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I. INTRODUCTION

In recent years, population increase due to natural birth and migration has led to unprecedented growth within cities around the around. China, for example, is a country with vast territory, but economic development and population growth continue to reduce available land resources, (Sheng et al. 2017). This has led to land reclamation by pumping and filling in the eastern coastal regions to meet the needs of urbanization. However, large areas of reclaimed land need rapid drainage consolidation treatment leading to deformation, (Xue et al. 2015).

The reclaimed soil is often high in water content and salinity or salt and has zero or extremely poor shear strength, (Liu yiming et al. 2018). It cannot bear any loads. To overcome this problem, civil engineers have developed several soil improvement techniques. These include, but are not limited to, soil vibration, cement mixing, vacuum preloading, dynamic loading, (Jie Han et al. 2015). However, most of these methods are heavy dependant on the size of soil particles, water content and depth of soil for strengthening or improvement. Additionally, they require heavy equipment, long treatment times and often struggle to achieve the desired effect on some problematic soils.

Discovered in 1809 by Rues F. F, electro-osmosis is the movement of water due to the application of a direct current within the soil. Water moves from the positive electrode (anode) to the negative electrode (cathode). This leads to a negative pore water pressure being developed at the anode leading to a reduction in pore water pressure to negative and eventually causing consolidation, deformation and an increase in the shear strength of the soil. Electro-osmosis is therefore an idle ground improvement method for high water content soils such as clays and silts. Research shows that soil improvement via electro-osmosis is permanent, (Miligan et al. 1995; Thomas and Lentz et al. 1990; Holtz et al. 2001).

The Advantages of electro-osmosis include but are not limited to; does not depend on soil particle size (e.g., clays and silts), unaffected by soil water content, may be configured to meet desired soil requirements, reduced dependence on void ratio, electro-osmosis is not affected by low shear strength of soils and does not require heavy machinery.

Despite these advantages, electro-osmosis is not without its flaws. These disadvantages include; electro-osmosis has high power consumption, dependent on the electrode material, lack of a proper standardized test and an accurate analytical calculation procedure as well as leads to uneven vertical deformation.

To overcome the deficiencies of electro-osmosis, several scholars have proposed incorporating electro-osmosis with different ground improvement techniques such as vacuum preloading and additional of chemical stabilizsers, (Mohamedel and Shang et al. 2002; Indraratna et al. 2012; Liu et al. 2018). While these combination methods have reported an improvement in electro-kinetic treatment of soil, they are often difficult to replicate and maintain. Additionally, they may result in increased soil pollution and do not provide adequate research on the consolidation and deformation of soil mass,

In recent years, studies concerning soil improve by means of electro-osmosis combined with surcharge has been carried out, (Silvana Micic, 1998; Liu et al. 2016; Fan et al. 2018). The research focus of the combined method of electro-osmosis and loads has been to increase electro-osmotic dewatering. Furthermore, the most effect method of electro-osmotic soil treatment when combined with surcharge and coupled with electrode arrangement is yet to be studied.

Therefore, this article aims to study/investigate the effects of consolidation and deformation of Hangzhou sludge under electro-osmosis. To further increase electro-osmotic efficiency, electrode arrangement (one-dimensional, two-dimensional and hexagonal one-dimensional) and surcharge loading were taken into account. Observations were performed from the perspective of the electro-osmotic effect and the results were also compared with the published literature. Interpretations of distinguished behaviours and inconsistencies are provided on the basis of an overall comparison and analysis.

II. MATERIAL AND EXPERIMENT DETAILS

Material Properties

The soil sample was obtained from a foundation pit in Hangzhou city, Zhejiang province China. Soil obtained is classified as fine silt (Hangzhou sludge). Physical properties of the soil are presented in Table 1, the tests were carried out according to the available laboratory equipment in line standard code GB T0103-2019.

Table 1 Physical properties

Specific gravity G_s	Void ratio e	water content $w/\%$	saturation S_r	Liquid limit $w_L/\%$	Plastic limit $w_P/\%$
2.68	1.50	49.60	85	41.54	23.0

Apparatus and procedures

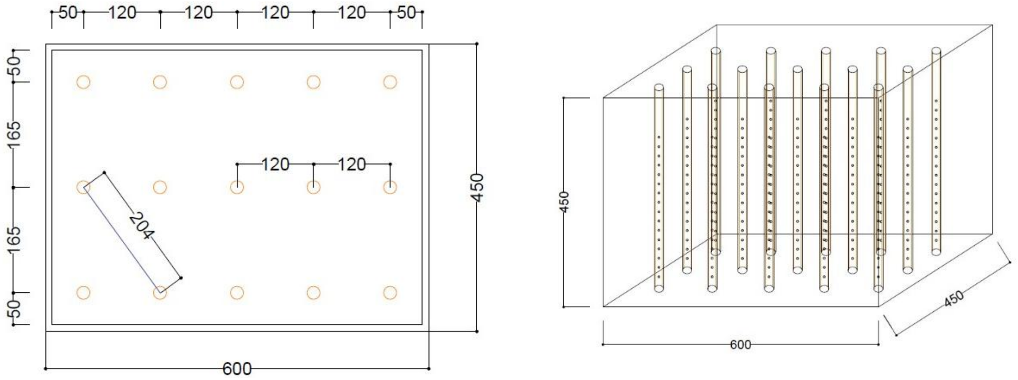
To investigate the most effective combination of the electro-osmosis methods and preloading, a total of six types of tests were performed comprised of one-dimensional electrode arrangement of electro-osmosis only and combined method (T1 and M1), two-dimensional electrode arrangement with electro-osmosis only and preloading (T2 and M2), and hexagonal-one dimensional electrode arrangement tests (T3 and M3). The test schemes of all six tests are shown in Table 2.

Table 2 Main experimental program

Testing Set/ Number	Testing Voltage/ V	Moisture Content of soil (%)	Surcharge (yes or no)	Experiment Duration (hours)
T1	25	71.7	no	72
M1	25	70.56	Yes	72
T2	25	69.5	no	72
M2	25	71.1	Yes	72
T3	25	70.0	no	72
M3	25	70.1	Yes	72

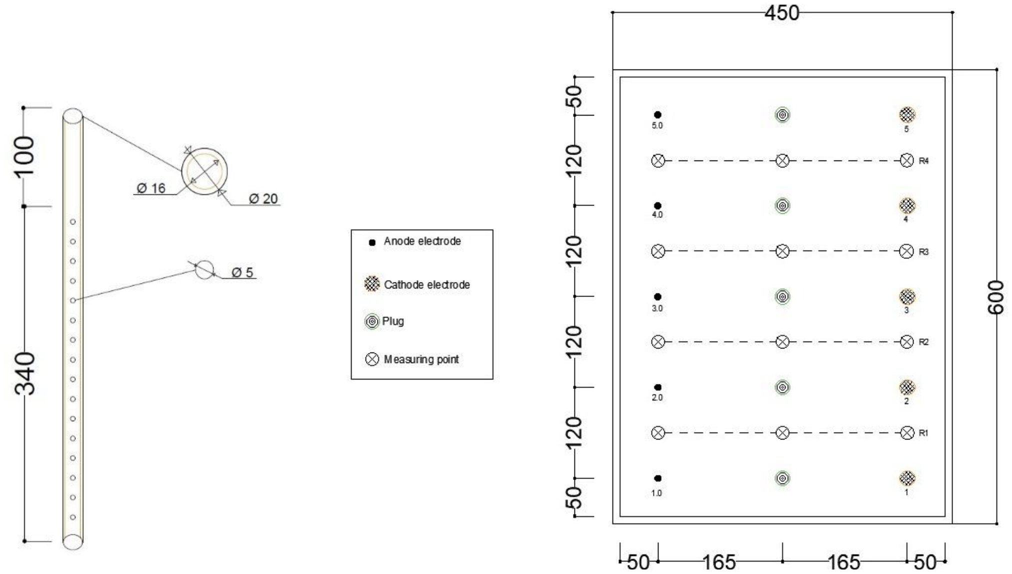
A self-made testing model was designed and manufactured for this study. A schematic diagram of the model is shown in Figure 1 (a) and (b). Its dimensions are; length 600mm, width 450mm and height 450mm. The rectangular model tank was made of plexi-glass and wrapped with a steel frame to increase its strength. The material transparency of the self-made box enabled clear monitoring of the soil level during consolidation and deformation, while the soil was undergoing electro-osmotic treatment.

Hollow synthetic plastic-tubes measuring 440mm in length, with inner diameter of 16mm and outer diameter 20mm are used for drainage of water during electro-osmosis as shown in figure 2 (a). They are perforated with approximately 17 small holes measuring 5mm in diameter along two sides. During electro- osmosis, water accumulated in the vicinity of the cathode, flowed to the bottom and was drained into measuring containers each able to hold 500ml of water. During the test, the volume of the discharged water and drainage rate of the probes were monitored every four hours and Afterwards the water content, deformation and cracks were measured. The moisture content of the top and bottom layer of the soil was measured after soil treatment. The measuring points during the experiment are shown in Figure 2 (b). They are divided into three main regions; anode, middle and cathode region. The anode region is around the anode electrodes. The cathode region is around the cathode electrode and the middle region is the area in between the anode region and the cathode region. Furthermore, the measuring points are placed in four rows in the soil mass, R1 to R4, between the rows of the anode and cathode electrodes.



(a) Top elevation (b) Side view

Figure 1. Schematic diagram of the model showing electrode positions



(b) Hallow plastic tube (b) Test measuring points

Figure 2. Schematic diagram of electrode and measuring area

Fine steel wire is wrapped around the hollow plastic-tubes and acts as the cathode electrodes while plain steel bars measuring 8mm in diameter are used as anodes. The desired water content percentage of the soil for the study is 70%. An Oulaide 220V 950r/min hand mixer, was used to thoroughly mix the soil and water to form a clay slurry. The method of fast heating using alcohol was selected to measure the water content, the overall water content error rate was maintained within +-2%. A fixed weft spd-3606 DC power supply unit was used to supply power to the electrodes. The spd-3606 DC power supply provides three independent outputs and CH1/CH2 dual output ranges (30V / 6A or 60V / 3a) and a voltage gradient of 25V corresponding to a voltage potential of 1.25 V/cm and total experiment running time was 72 hours for each test.

Description of Soil Specimen

After collection, the soil was placed within plastic containers under room temperatures in the storage unit and left untouched for one week. Afterwards, water was slowly added to the sample until approximately 5mm above the soil. The container was then covered and left untouched for not less than 24 hours. Geotextile measuring 0.3mm thick with good performance is cut using scissors into a rectangle measuring 340mm long and 100 mm wide. The geotextile is then wrapped around each cathode drain pipe. Thereafter, fine wire is tightly wound and tied from bottom to top to ensure the test soil sample has electricity at any depth from the bottom to the surface during the test.

During electro-osmosis only test (T1, T2 and T3) a layer of Vaseline is applied inside the model box, and the soil sample is loaded in compacted in layers with a height of 10mm. This ensures that the test soil sample is uniformly dense and test error is minimised. The treatment depth set in this test is 24.5cm. Additionally, plugs are used prevent water and soil from sipping out of the unused holes.

The process of sample preparation and loading of the combined method tests (M1, M2 and M3) is the same as that of electro-osmosis only (T1, T2 and T3). However, a layer of geotextile is laid on the surface of the soil sample to prevent cracks during the development of electro-osmosis. This is to avoid the sand, as a vertical load, falling into cracks and causing unnecessary errors to the test. Additionally, fine sand with a density of 1.8g/cm^3 is placed over the soil sample in the model box. According to equation 1, the design of uniform load, q, is related to the density of sand and the height of pile load, H. In this test, the density of fine sand used is 1. 8g/cm^3, while the designed stacking height is 10 mm. Therefore, the calculated uniformly distributed load q is 1.76 kPa.

$$q = \frac{F}{S} = \frac{mg}{S} = \frac{\rho v g}{S} = \rho g h \qquad (1)$$

III. RESULTS AND DISCUSSIONS

The influence of the different electrode materials is analysed and compared from the perspectives of the electro-osmotic effect. Specific items include cumulative discharge, drainage rate, water content (upper and subsoil layer) and crack patterns. Detailed descriptions of the results are presented as follows.

(a) Drainage Rate

The greatest increase and decrease in drainage rate occurred between 30 and 60 hours of experiment time in both T1 and M1. T1 recorded its highest drainage rate at time 32 hours (1210.75 ml/h), followed by its slowest drainage rate at 40 hours (170.75 ml/h). In comparison, M1 recorded a much higher drainage rate than T1, the highest drainage rate occurred after 36 hours of experiment time (1800.74 ml/h), while the slowest rate of drainage rate recorded after 32 hours of testing was recorded as 501.74 ml/h at 60 hours and is shown in figure 3.

Regarding experiments T2 and M2, it can be noticed from figure 4 that during the first ten hours of the experiment, there was a constant rapid increase in the drainage rate followed by a slight decrease in both electro-osmosis and electro-osmosis combined with loads. The greatest increase in drainage rates in both experiments was noted between 10 and 24 hours. During this period (10-24 hours), a rapid increase in drainage rate was followed by a slight decrease and then finally resulted in the highest increase in drainage rate in both experiments. T2 had a maximum drainage rate of 2383.745 ml/h at 12 hours and M2 2682.64 ml/h at 20 hours, with the data of M2 12.5% higher than that of T2.

Experiments T3 and M3, at 20 hours of experiment time, the highest drainage rate per hour in both electro-osmosis only (789.29 ml/h) and electro-osmosis combined with surcharge (674.355 ml/h) was recorded. Figure 5 shows the drainage rate of T3 and M3, it was observed that M3 recorded a lower maximum drainage rate than T3. At the hours ranging between 20-36, there was a decrease in drainage rate in both T3 and M3. However, the overall drainage rate of electro-osmosis only experiment was still greater than that of the combined method.

Electro-osmosis combined with surcharge (M3) experienced a more gradual decrease in drainage rate after 20 hours of experiment time compared to T3. After 36 hours of experiment time, the drainage rate of M3 was recorded to be higher than that of T3 up until the end of the experiment at 72 hours. The lowest drainage rates of T3 and M3 after 36 hours were 424.53 ml/h and 489.44 ml/h respectively. This means that M3 was able to maintain a much better drainage rate over an extended period of time.

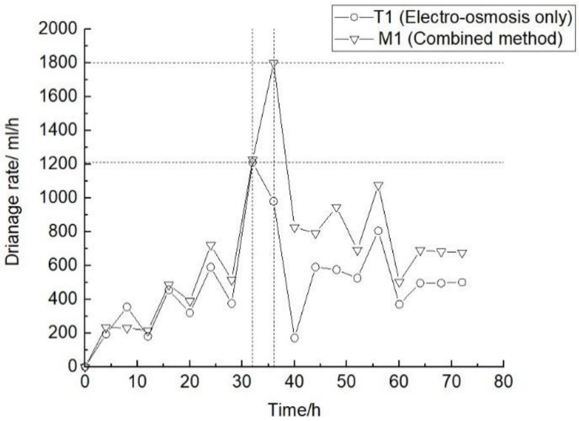


Figure 3. Drainage rate of T1 and M1

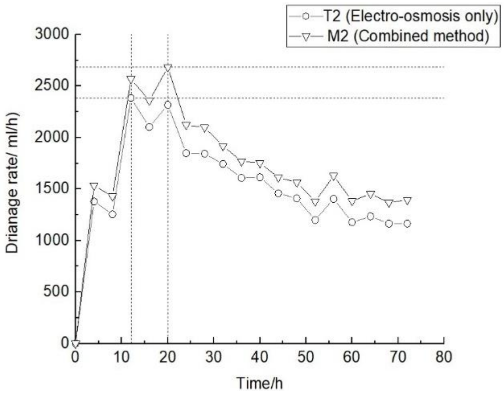


Figure 4. T2 and M2 drainage rate graph

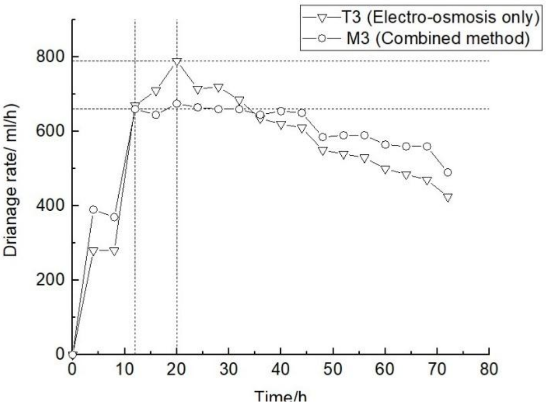


Figure 5. T3 and M3 drainage rate graph

(b) Cumulative Discharge

During the first 30 hours of the experiment, there was a steady increase in total drainage with a slight difference between T1 and M1. A rapid but steady increase in cumulative discharge was experienced in both experiments. After 32 hours of testing, the difference in discharge between experiment T1 and M1 begun to increase. Furthermore, the difference in cumulative drainage between M1 and T1 was more clearly defined after 32 hours of experiment time. The increase in accumulated drainage continued up until the end of the experiment. M1 had a total discharge of 15,357.5ml while T1 had a discharge of 11058.4ml. The combined method (M1) discharged 28% more water than the electroosmosis only (T1) Figure 6 shows the discharge volume of T1 and M1.

Steady increase in the cumulative drainage was experienced in both experiment T2 and M2. A steady difference in volume discharge begun to occur after 8 hours. At the end of the experiment, the total cumulative drainage of T2 was 35523ml. M2 recorded a total cumulative drainage of 40546.6ml, which was 12.9 percent higher than that of T2 and maybe seen in Figure 7. It is important to note that this two-dimensional arrangement had at least twice as much cumulated discharge in both T2 and M2 experiments as compared to the one-dimensional electrode arrangement of experimentsT1 and M1.

Cumulate discharge graph of T3 and M3 with one-dimensional hexagonal electrode arrangement may be seen in figure 8. The graph shows that the cumulative discharge was directly proportional to time. Total volume discharge of T3 was 11856.42 ml and M3 had 12731.88 ml respectively. Despite T3 having recorded a higher maximum drainage rate at time 20 hours, M3 experienced a higher discharge volume consistently during the experiment.

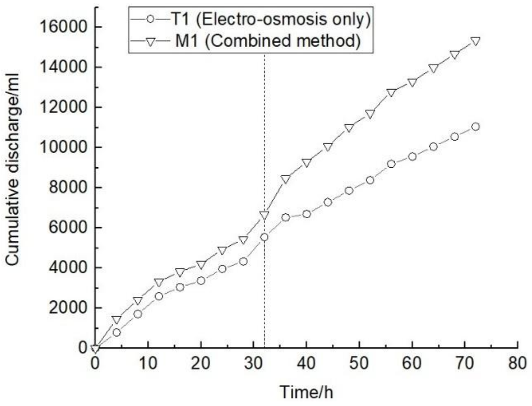


Figure 6. T1 and M1 total cumulative drainage

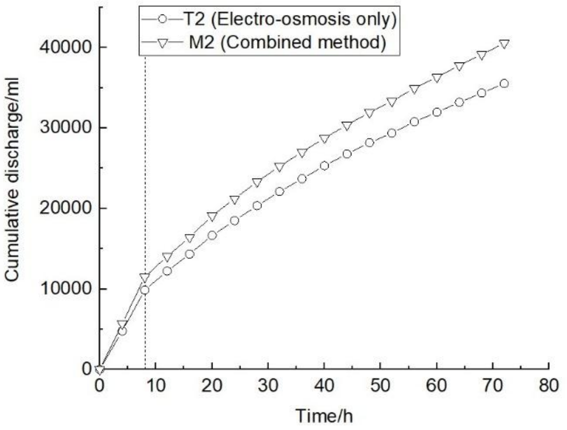


Figure 7. Cumulative drainage graph of T2 and M2

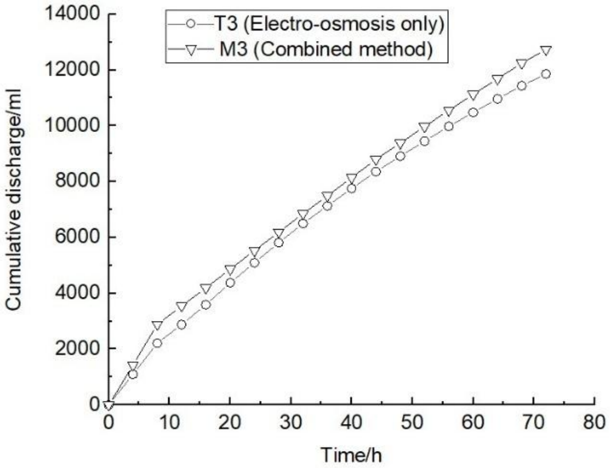


Figure 8. T3 and M3 cumulative drainage graph

(c) Water Content

Upper soil T1 and M1

Water content readings were measured after the end each of the six experiments. T1 and M1, water content tests were carried out at the cathodic, middle and anodic areas. The measuring points were carried out at 0mm, 165mm and 330mm from the cathode electrode. The water content was measured in both the upper soil layer approximated 2cm (20mm) from the surface, and subsoil layer approximately 11cm (110mm) from the surface in both experiments T1 and M1.

From the cathode towards the anode, there is a decrease in water content in both T1 and M1 as shown in figure 9. The lowest water content in the upper soil in both experiments was recorded in the middle region of the soil mass, T1 (32.8%) and M1 (32.98%) respectively. While the water content readings of the anodic regions of T1 and M1 was 35.88% and 35.83%.

There was a slight difference in water content percentage between the anodic area and the middle of the soil mass in both T1 and M1. Additionally, the cathodic area had the highest water content reading, where electro-osmosis only coupled with one-dimensional electrode arrangement recorded 34.74% and the combined method 39.16%. The general trend in both experiments T1 and M1 was that a small increase in water content was noticed at the anode compared to the middle of the soil layer.

During the experiment, compression in the soil mass increased due to the self-weight of soil and loads provided by the layer of sand from above. Under this electrode arrangement, water was only allowed to drain at the cathode in both T1 and M1. However, besides electro-osmosis, the force created by the surcharge may have caused an additional negative pour water pressure within the soil mass. Therefore, water at the bottom of the anode electrode begun to gradually move upwards with time. This means that while electro osmosis caused a movement of water from the anodic area to the cathode, there was an additional movement of water upwards within the soil mass. The water in the middle area of the soil mass, being closer to the cathode experienced a much faster movement of water than the anodic region and hence a faster decrease in volume. Due to this, water movement from the anode region to the cathode may have slowed down as the drainage volume within the middle area begun to decrease. Hence, resulting in a slightly higher water content in the area surrounding at the anode electrodes compared to the middle area. The cathode area recorded the highest amount of water content. This is attributed to the fact that under the process of electro-osmosis, water is drained at the cathode, hence during experiments T1 and M1, the area around the cathode had a higher water content percentage in the upper soil layer.

Subsoil Layer T1 and M1

Figure 10 shows the water content percentage of T1 and M1 in the subsoil layer of the soil mass. Similar to the phenomena that occurred in the upper soil layer, the water content percentage decreased as you moved away from the cathode. The lowest water content was recorded at the middle area of the subsoil, while the anodic area also recorded a lower water content than the area surrounding the cathode.

M1 experienced a more uniform decrease in water content in the subsoil layer as you moved away from the cathode compared to T1. M1 had an overall lower percentage of water content at both the cathode (45.59%) and anodic area (35.43%), compared to (55.56%) and (40.73%) recorded in the cathode and anode region of experiment T1. This means that with regards to one-dimensional electrode arrangement, more water in the subsoil region is drained in the electro-osmosis combined method (M1) than the electro-osmosis only method (T1).

Upper Soil layer T2 and M2

T2 and M2 water content readings were taken at distance measuring 0mm, 82.5mm and 165mm from the cathode in the upper and sub soil layer. In both T2 and M2, the water content readings in the upper layer were taken at 2cm(20mm) from the surface. Additionally, the subsoil water content percentage was recorded at 11cm(110mm) from the surface in both experiments. The figures 11 and 12 show the results of the water content tests in the upper and lower layers of the soil mass in both electro-osmosis only and electro-osmosis combined with surcharge under two-dimensional electrode arrangement.

The lowest percentage of water content in the electro-osmosis only and combined method were 24.73% and 29.27% respectively, recorded at the middle area of the soil mass. The difference between the water content of the upper soil of the anode region (31.97%) and the upper soil layer of the middle region (29.27%) in experiment M2 was slight. Therefore, it can be assumed that the combined method was more effective in draining water across the entire upper layer of the soil mass.

Despite an even decrease in water content in M2, T2 recorded a lower water content percentage in both the cathode (27.74%) and middle (24.73%) region of the soil mass. This difference in the water content, i.e., the higher water content in the upper layer of M2 as compared to T2, maybe attributed to the upward movement of water in the soil due to the pressure exerted by the surcharge.

The highest water content percentage, 57.25% was recorded at T2 anodic area. This means that while the electro-osmosis only method was efficient in draining the water at the cathode and middle regions, overtime, it was not as efficient in draining water further away from the cathode. Furthermore, the large difference in water content in T2 may mean that two-dimensional electrode arrangement under electro-osmosis only results in more complex physio-chemical reactions within the soil. These reactions may lead to a difference in the drainage of water from the cathode to anode region of the upper soil layer.

Subsoil Layer T2 and M2

The middle area had the lowest recorded percentage reading at 35.87% in the lower soil layer of experiment M2. The anodic area however recorded a higher percentage of 41.57%, lower than the cathode area (44.23%). It can be seen from the results that the overall difference in water content in M2 across the subsoil layer was not high. This means that the combined method resulted in a more uniform distribution of water across the subsoil layer.

During the M2 experiment, the change in volume of the middle area occurred faster than other regions of the soil. This is due to the combined action of electro-osmosis and loads, resulting in a slow drainage of water from the anode electrode through the middle layer over time. Hence, the anode area had a slightly higher water content (41.57%) than the middle area (35.87%).

Electro-osmosis only method had the lowest water content reading (20.61%) in the subsoil at 165mm away from the cathode electrode. The middle area recorded a higher water content percentage than both the cathode and anode. This is because the anode electrodes of two-dimensional arrangement resulted in a much faster water drainage than the cathodes electrodes in the middle area of the soil mass.

Water drainage within the soil mass was more even over time, resulting in a small difference in volume of the middle (38.03%) and cathodic (41.34%) areas.

Experiment T2 recorded lower average water percentage readings in both the upper and lower soil layers than M2. However, the difference in water content percentages across the soil mass (cathode, middle and anode area) was lower in M2 than T2. Therefore, M2 drained water in a more uniform manner in both upper and lower soil layers compared to T2 which experienced large differences in water content readings.

Upper soil layer T3 and M3

T3 and M3 water content readings were measured below the soil surface at 2cm(20mm) (upper soil) and 11cm(110mm) (subsoil). At distances measuring 0mm, 99mm and 198mm from the cathode. Figures 13 and 14 how the upper and lower soil water content reading of T3 and M3. A small difference in water content was observed in the upper soil layer of the hexagonal one-dimensional electrode arrangement tests (cathode (49.41%), middle (50.7%) and anode (50.0%). M3 experienced little difference in water content readings, in the upper soil layer. However, the lowest water content percentage (37.5%) was measured at distance 99mm (middle area) in T3. In T3, the water content percentage at the cathode and anode area was much higher than that at the middle region of the soil mass in the upper layer. This means that T3 is most effective in discharging water in the middle area of the upper layer.

Subsoil Layer T3 and M3

Within the subsoil layer, the water content percentage of M3 across all regions (cathode, middle and anode) was lower than that of T3. The lowest water percentage in both T3 and M3 was measured in the middle area at a distance of 99mm from the cathode electrode. This was 41.86% (M3) and 44.44% (T3) respectively. Meaning, the combined method electro-osmosis and surcharge is more effective in discharging water in the subsoil layer than electro-osmosis only method. Furthermore, it was noted in both M3 and T3, that the anode region had the highest water content percentage

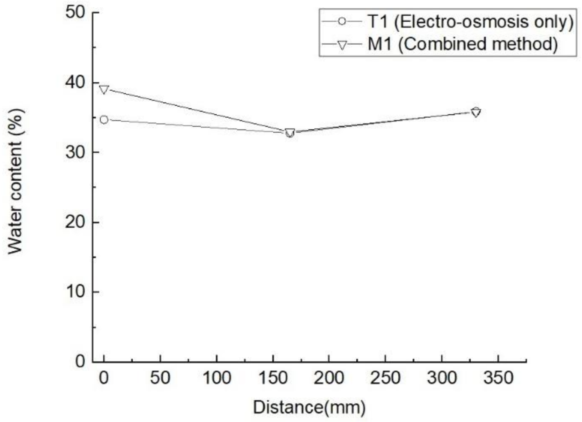


Figure 9. Upper soil layer water content of T1 and M1

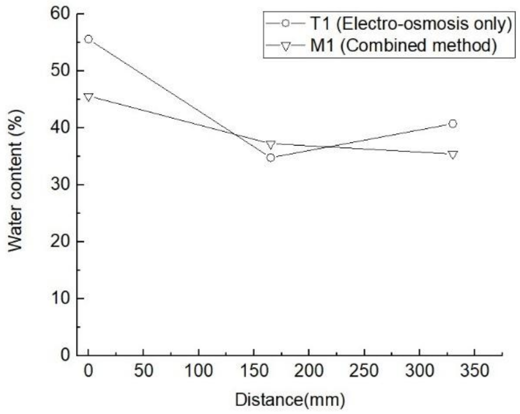


Figure 10. Subsoil layer water content T1 and M1

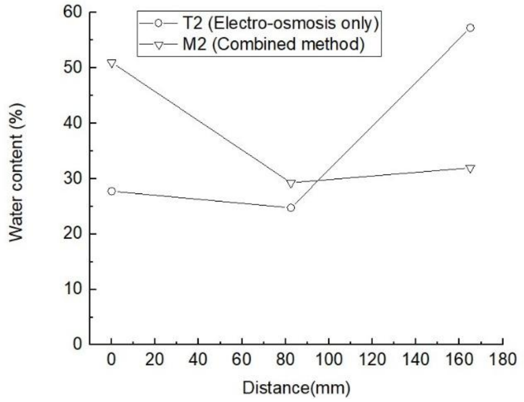


Figure 11. Upper layer water content of T2 and M2

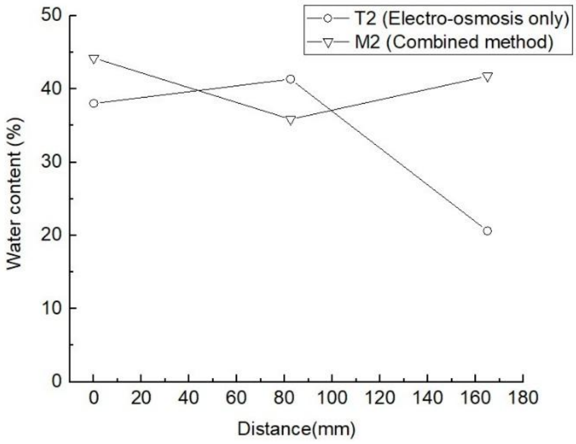


Figure 12. Subsoil layer water content of T2 and M2

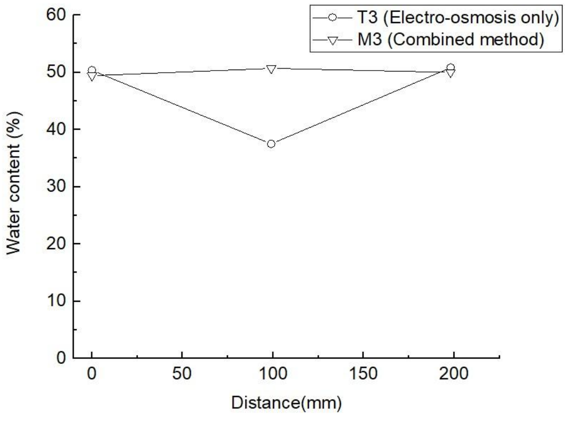


Figure 13. Upper soil later water content of T3 and M3

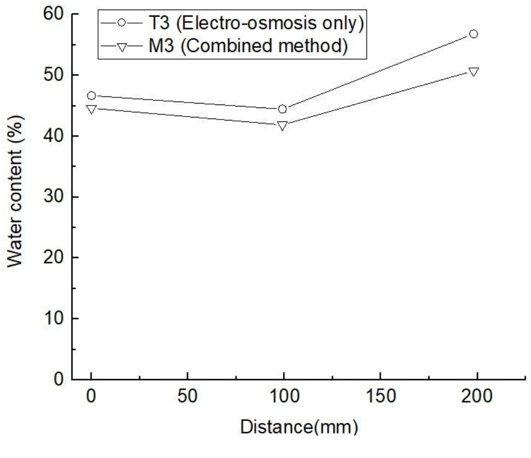


Figure 14. T3 and M3 subsoil layer water content

(d) Soil Deformation

One Dimensional Electrode

Under the one-dimensional electrode arrangement experiments of T1 and M1, the vertical and horizontal deformation after the experiment was recorded across the soil mass and the average settlement figures obtained. The vertical deformation was recorded at the cathodic, anodic and middle area of the soil mass and may be seen in the figure 15.

Vertical Settlement occurred at all points measured in both experiments. As you moved away from the cathode, the vertical settlement begun to increase, resulting in the middle area experiencing the highest settlement in both experiments T1 and M1 of 55mm and 80.5 mm respectively. While the anode region experienced the lowest vertical settlement in both experiments T1 and M1.

Horizontal deformation was experienced only at the anodic region of both the electro-osmosis only and electro-osmosis combined with surcharge. A total horizonal deformation of 11.5mm and 10.5mm was measured at T1 and M1 respectively. As you moved away from the cathode, the vertical deformation begun to increase, with the largest vertical settlement being recorded at the middle of the soil layer in both experiments. However, afterwards, as you moved further away from the middle of the soil mass, the vertical settlement begun to decrease. The lowest settlement occurred at the area surrounding the anode electrodes.

Two-Dimensional Electrode Arrangement

Under two-dimensional electrode arrangement, the horizontal and vertical deformation of T2 and M2 were measured respectively. Figure 16 shows the vertical settlement of both electro-osmosis only and electro-osmosis combined with loads, measured at 0mm, 82.5mm and 165mm from the cathode electrode.

It was observed from Figure 16 that the middle and cathode regions of the electro-osmosis only method resulted in a higher vertical deformation of 46.1mm and 51.5mm respectively. This was slightly greater than that of the combined method, 42.88mm at the middle area and 46.5mm at the cathode electrode.

Figure 16 shows that the soil vertical settlements decreases in distance from the cathodes. This is attributed to the electrode arrangement, where the cathode electrodes were at the centre of the soil mass. And the largest vertical deformation was recorded at the cathode electrode in both experiments T2 and M2. This is due to the fact that the middle of the soil mass experiences the largest distribution of loads in the soil mass.

The lowest vertical settlement readings occurred at the anode electrode in both experiment T2 and M2, with experiment M2 recording a higher average vertical deformation reading of 27.33mm compared to 18.33mm of T2. This means that under the action of the combined method, vertical settlement is distributed more evenly across the soil mass.

One-Dimensional Hexagonal Electrode Arrangement

Horizontal deformation occurred on two sides of the self-made box in T3. The figure 17 shows the settlement graph of both experiments, measured at the cathode, middle and anode measuring points. Vertical settlement was recorded at distances 0mm, 99mm and 198mm from the cathode electrode.

As you moved further away from the cathode electrode, an increase in vertical deformation of the soil mass was recorded. The anode region recorded the highest average vertical settlement in both M3 and T3, 48.4mm (combined method) and 29.17mm (electro-osmosis only.) With regards to the vertical settlement, experiment M3 recorded a 39.73% higher vertical settlement than T3.

A large difference between the vertical deformations in the cathode, middle and anode regions of the soil mass in T3 was recorded. This was not the case when compared to M3. It may be concluded than the vertical settlement in M3 was not only better, but more even than that of T3. Overall, one-dimensional hexagonal electrode arrangement recorded a much more even vertical deformation than one-dimensional and two-dimensional electrode arrangements.

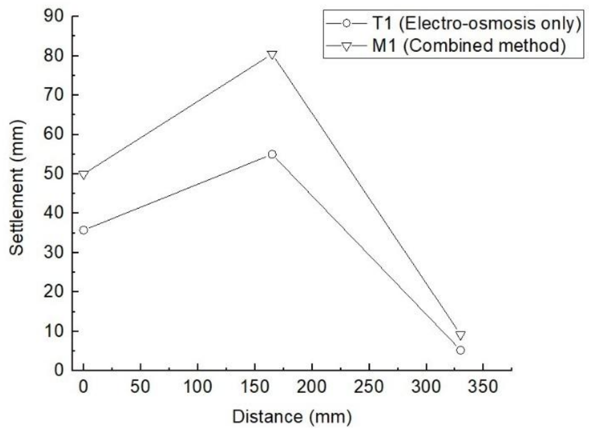


Figure 15. T1 and M1 vertical deformation

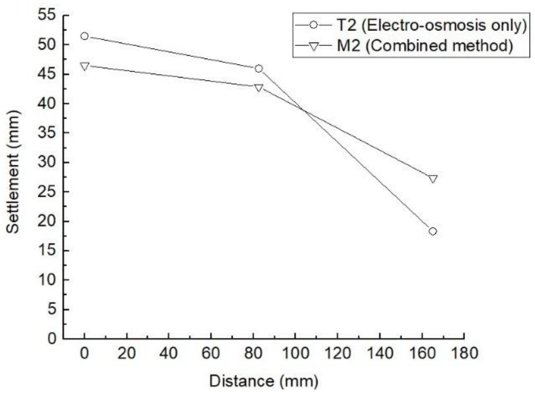


Figure 16. Vertical deformation of M2 and T2

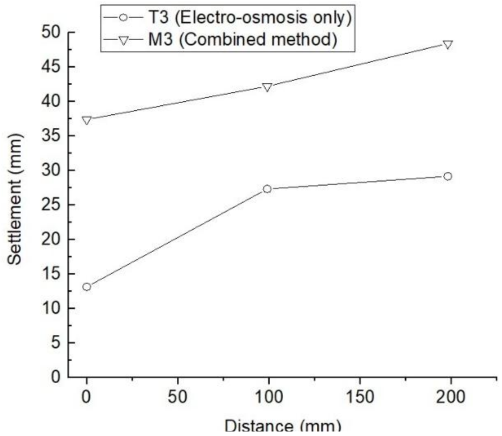


Figure 17. Hexagonal one-dimensional arrangement vertical deformation

(e) Cracks

The figure 18 (a) and (b) show images taken after the end of the experiments T1 and M1. Cracks were seen at both the anode and cathode electrodes. Electro-osmosis combined with surcharge resulted in less crack formation compared to the electro-osmosis only method. Regarding experiment T1, more cracks appeared at the anode electrodes than the cathode electrodes. Less cracks were experienced at both the anode and cathode of M1 compared to T1.

The crack pattern at the anode electrodes of experiment T1 mostly occurred in three directions away from the electrode. Cracks were noticed at the cathode as well, however, the cracks at the cathode were smaller than those at the anode for the electro-osmosis only experiment. The combined method (M1) experienced very small cracks at the anode electrode. Almost no cracks appeared at the cathode.

Two-dimensional electrode arrangement, led to the development of a semi continuous crack all along the cathode electrode in both T2 and M2. However, the crack at the cathode under the combined method was much smaller than that of T2. The Figure 19 (a) and (b) shows photos that were taken at the end of both experiments T2 and M2 respectively. It was observed that the cracks developed at T2 cathode electrodes were much larger than those of M2, it may therefore be concluded that the under the two-dimensional electrode arrangement, the combined method if efficient in reducing crack development, especially around the cathodic electrodes.

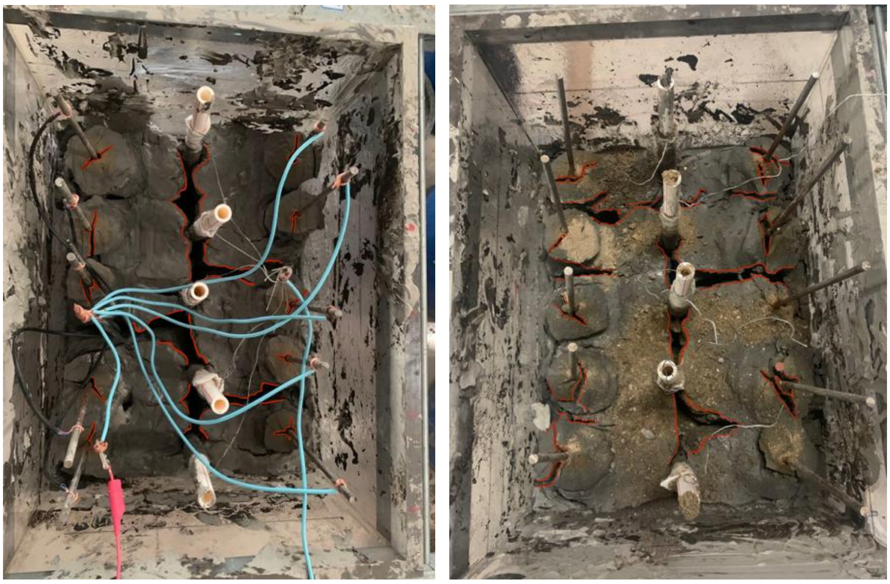
Horizontal deformation was experienced at all four sides of the self-made box in both experiments T2 and M2. At sides 1,2,3 and 4, electro-osmosis combined with surcharge recorded and average horizontal displacement of 18mm, 25mm,10mm and 34mm respectively. Experiment T2 (electro-osmosis only) recorded a horizontal displacement of 26mm, 23.3mm,12mm and 25.7mm, at 1, 2, 3 and 4 electrode sides. Under two-dimensional electrode arrangement, it may be noted that the combined method of electro-osmosis with loads, was not sufficient to warrant a large difference in horizontal deformation compared to electro-osmosis only method.

The figure 20 (a) and (b), are photos of T3 and M3 after the experiments were concluded. It is evident from the figure that more cracks appeared in electro-osmosis only compared to the combined method. Therefore, under one-dimensional hexagonal electrode arrangement, combined method is capable and effective at reducing cracks within the soil mass.

In experiment T3, three major cracks appeared around the cathode. The largest crack had a maximum width of 7cm(70mm). While M3 had minimal cracks all around the soil mass, and recorded slight soil depressions on the left and right side of the cathode electrode.

(a) T1 crack formation (b) M1 crack formation

Figure 18. Cracks after experiments



(a) T2 crack pattern (b) M2 crack pattern

Figure 19. T2 and M2 cracks after experiments

(a) T3 crack pattern (b) M3 crack pattern

Figure 20. T3 and M3 crack pattern after experiments

IV. ANALYSIS AND DISCUSSION

Based on the analyses of drainage rate, discharge volume, water content, deformation and cracks, it has been shown that the addition of surcharge, regardless of electrode arrangement produces better performance during electrokinetic phenomena compared to electro-osmosis only method. It was observed throughout each experiment, that the drainage rate did not immediately decrease with time. A maximum calculated increase in drainage rate was observed at different times during both electro-osmosis only and combined method experiments. T1 had a maximum drainage rate of 1210.75 ml/h at time 32 hours. T2 recorded 2383.75 ml/h at time 12 hours, while T3 had 789.29 ml/h after 20 hours. The highest drainage rate due to electro-osmosis only was observed in T2. Therefore, it may be concluded that with regards to electro-osmosis only, T2 with two-dimensional electrode arrangement had the best drainage rate with time.

Electro-osmosis combined with surcharge was involved in experiments M1, M2 and M3. The maximum drainage rate readings are as follows; M1 had 1800.74 ml/h at 36 hours, M2 2682.64 ml/h after 20 hours and M3 674.36 ml/h at time 20 hours. Total drainage rate of all six experiments is shown in Figure 3.19. Therefore, the highest drainage rate was observed in experiment M2. T2 and M2 had the highest drainage rates due to the number of electrodes within the soil mass (5 cathode, 10 anodes) which had direct contact with the soil. Decrease in drainage rate is attributed to increased electro-osmotic resistance at the electrodes within the soil mass.

Cumulative discharge of electro-osmosis only experiments after 72 hours were as follows; T1 (11058.41 ml), T2 (35523.04 ml) and T3 (11856.42 ml). Total cumulative discharge readings of electro-osmosis combined with surcharge was as follows; M1(15357.53 ml), M2 (40546.59 ml) and M3 (12731.88 ml). During this study, the closed anode and open cathode drainage method was adopted. Therefore, due to electro-osmosis, water molecules within the soil mass moved towards the cathode electrode where they are drained and no drainage is permitted at the anode electrodes. M2 and T2 reported the largest volume discharge, this is because of the increased contact between the electrodes and the soil compared to the other experiments. Furthermore, M2 discharged a higher water quantity, thus proving that the combined method is more effective for total water discharge within the soil compared to electro-osmosis only.

Upper and subsoil water content readings were taken in each experiment category at 20mm (2cm) and 110mm (11cm) below the surface of the soil layer. Compared to the original water percentage of roughly 70%, all tests recorded lower water content readings at the end of the experiments. Furthermore, in the upper soil layer, T2 had the lowest water content percentage, while in the subsoil, M1 had the lowest water content reading. The observed inhomogeneous distributions of water content within the soil illustrated non-uniform soil enhancement during electro-osmosis as reported by other scholars such as (Chew et al. 2004) and (Xiao et al. 2018). Compared to the original value, significant changes of water content are observed near the anode and the cathode. This is attributed to gas bubbles produced by electrolysis at the electrodes, caused by the contact between electrodes and the soil.

Soil deformation in the horizontal (side movement) and vertical directions were measured. According to the Terzaghi principle of effective stress, under the condition of unchanged total stress, the effective stress will increase in the case of decreased pore water pressure. After that, soil void ratio decreases, leading to consolidation and settlement of soil. The average vertical deformation in the soil mass of the electro-osmosis and combined methods were; T1 (32.02 mm), T2 (38.61 mm), T3 (23.22 mm), M1 (46.58mm), M2 (38.92 mm) and M3 (42.67 mm). Figure 3.21 shows the average vertical settlement of all six experiments. One-dimensional electrode arrangement combined with surcharge method (M1) had the largest average vertical settlement across the soil mass. The high permeability resulting from electro-osmosis combined with surcharge in M1 accelerated the dissipation of pore pressure in the soil mass and provided better route for discharging of water, consequently, resulting in a quick consolidation and a large settlement magnitude. However, due to electrode spacing, it was also observed that one-dimensional electrode arrangement (T1 and M1) had the most uneven vertical settlement compared to two-dimensional and hexagonal-one dimensional electrode arrangements. Furthermore, the hexagonal-one dimensional electrode pattern experiments had the most even vertical deformation across all areas of the soil mass.

Horizontal deformation occurred on all four sides of the self-made box in experiment T2 only. One sided horizontal deformation occurred in both T1 and M1, while T3 experienced horizontal settlement on two of the four sides of the self-made box. Furthermore, no horizontal deformation was observed in M3. As reported in engineering practices, the ground moves laterally inward during electro-osmosis. Lateral inward deformation deceased under the combined method compared to electro-osmosis only, which implies that surcharge can reduce the lateral movement caused by electro-kinetic phenomena.

Each electrode arrangement yielded a different crack pattern within the soil mass. It was evident that the cracks developed under the combined method experiments were much less than those observed under electro-osmosis only method. The largest cracks at the anodic electrodes were observed in T1, while T2 had significant cracks occurring at the cathode electrode. After 72 hours, M3 had the least cracks within the soil mass compared to all other electro-osmosis only and combined method experiments.

In addition to the above-stressed corrosion and electrochemical passivation, which reduce the effective contact between electrodes and soils, this study also observed the separation between the soils and the electrodes. This separation inevitably would decrease the contact regions of the electrodes and the soils, resulting in an increase in voltage loss. Other factors affecting the interface properties also include gas evolution and electrode decomposition. Gas is generated by the electrolysis of water, which can be denoted by the following reactions (with an iron electrode):

Crack formation results in the destruction of drainage channels, which were used for water moving. Decrease in rate of water movement within the soil Is reduced and the resistance to water was increased. Therefore, decrease in crack sizes under the combined method, resulted in improved the treatment effect under each electrode arrangement. Similar results were obtained by Shang et al. (2001) and Xue et al. (2015).

V. CONCLUSION

This research was carried out with the goal of better understanding the effects of electro-osmosis only as well as electro-osmosis combined with surcharge on soil consolidation and deformation. Experiments were carried out with different electrode arrangements; one-dimensional, two-dimensional and one-dimensional hexagonal patterns.

In total, six experiments were divided into three categories. Each category included electro-osmosis only and the combined method with a specified electrode arrangement. Total experiment time was 72 hours. During the tests, the drainage rate and cumulative discharge were recorded, while the water content, deformation, and crack patterns were observed at the end of each test.

It is observed throughout each experiment that the drainage rate did not explicitly decrease with increased time. Regarding the electro-osmosis only tests, the highest drainage rate was recorded in two-dimensional electrode arrangement with electro-osmosis combined with loads. This was followed by electro-osmosis only under two-dimensional electrode arrangement, while finally hexagonal one-dimensional spacing with surcharge. Among all combined methods, two-dimensional electrode arrangement had a higher drainage rate than both one-dimensional and hexagonal one-dimensional electrodes.

Total cumulative discharge of electro-osmosis with surcharge loads coupled with two-dimensional electrode arrangement is the highest of all six experiments. This was followed by the two-dimensional electrode arrangement with electro-osmosis only method. The lowest volume discharge was measured under one-dimensional electrode arrangement (electro-osmosis only).

Compared to the original water percentage of roughly 70%, each experiment recorded lower water content readings at the end of the experiments. Furthermore, in the upper soil layer, two-dimensional electrode spacing with electro-osmosis only had the lowest water content percentage, while in the subsoil, one-dimensional electrode spacing had the lowest water content reading of all six experiments.

The highest vertical deformation was recorded in electro-osmosis with loads coupled with one-dimensional electrodes, followed by combined method under Hexagonal one-dimensional electrodes respectively. Considering both electro-osmosis only and combined method categories, hexagonal one-dimensional electrode arrangement (electro-osmosis only) had the lowest but most even vertical settlement readings across the entire soil mass. Furthermore, electro-osmosis only coupled with one-dimensional electrode spacing was the only experiment to undergo horizontal deformation on all four sides of the self-made box, while hexagonal one-dimensional arrangement (with surcharge) had no horizontal deformation.

Electro-osmosis combined with surcharge experiments effectively reduced crack formations compared to the electro-osmosis only tests. Two-dimensional electrode arrangement without loads had the widest cracks, while hexagonal one-dimensional arrangement (with loads) had the fewest crack formation.

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