New Electrically Conductive Geosynthetics for Soft Clay Consolidation

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ABSTRACT: This paper seeks to discuss the performance of electro-osmotic consolidation in Singapore Marine Clay via prefabricated vertical drains (PVD) manufactured with electrically conductive polymer. Two series of laboratory tests were conducted under similar conditions with a constant voltage gradient of 100 V/m in order to compare the performance of the electric vertical drains (EVD) with the copper electrodes. Polarity reversal at 12-hour per cycle was implemented in the tests. Parameters studied in this series included shear strength, water content, current variation and energy consumption. Preliminary results showed that both electrodes exhibit similar trends. The electrical efficiency of the electrodes is assessed by the shear strength increment normalized by the energy supplied per unit volume of treated soil. The results show that creative use of conductive geosynthetics is a cost-effective alternative to the traditional treatment of soft clay.

1. INTRODUCTION

Novel usage and applications of geosynthetics can be envisaged by incorporating electro-kinetic phenomena with the traditional functions of geosynthetics materials. This entails the development of a new range of geosynthetics materials that are electrically conductive. Potential applications of electrically conductive geosynthetics include: in-situ decontamination of contaminated soils, electro-kinetic transport of nutrients in soil, treatment of incinerator ash from domestic waste, treatment of industrial waste, improvements in reinforced soil technology and the acceleration of consolidation of soft soil. Recently, an innovative electrically conductive prefabricated drain was reported (Chew et al., 2003). This product takes the advantage of PVD to provide vertical drainage as well as conductivity of the core to facilitate electric current flow into the soil enabling electro osmotic (EO) process. These special PVDs are referred to as the Electric Vertical Drains (EVD) in this paper.

EO is a process where flow of water between the soil particles is induced under an applied direct current electric field. EO based soil improvement is suitable for fine-grained soil (clay) which possesses a net surface negative charge. It would have more cations than anions within the pore fluid since excess cations are required to maintain electrical neutrality of the clay soil (Mitchell, 1993). Under an applied electric field, anions are attracted towards the anode while cations are attracted towards the cathode. As ions move, they drag along water of hydration and the surrounding free water by viscous force. In soil masses where there are excess cationic charges, there will be a net flow of cations towards the cathode which induces a flow of pore water towards the cathode. Hence, this will initiate the consolidation of clay via electro osmotic flow.

Research at the National University of Singapore (NUS) in collaboration with Jurong Town Corporation (JTC) of Singapore led to a field trial recently at the Tuas reclamation project to evaluate the preliminary performance of EO in marine clay (Chew et al., 2003). The field data showed very promising results. Further in-depth research was warranted in the relative performance of conventional copper electrodes versus the new conductive polymer products. This paper describes a study of EO consolidation in soft marine clay using copper and EVD electrodes. The comparative influence of these two different electrodes in terms of the current variation, voltage gradient, undrained shear strength, water content, and energy consumption is the main objective of this study.
2. TEST SETUP AND PROCEDURES

2.1 Electro-osmotic cells

A total of five model tanks were designed and assembled as electro-osmotic cells for EO consolidation study. The design comprised one EO cell having dimensions of 400 mm (L) x 400 mm (W) x 450 mm (H) and four others smaller cells of dimensions 400 mm (L) x 200 mm (W) x 450 mm (H). A schematic plan view of the EO cell including instrumentation is depicted in Figure 1.

EO cells were made of perspex, a non conductive material, to prevent short circuiting. The need for having five separate cells was to accommodate instrumentation and allow in-situ testing and extraction of samples at different times during treatment with least disturbance. To achieve that, soil was made homogeneous and all the five cells were subjected to same boundary, loading and electro-kinetic conditions. In order to carry out tests and sample extractions at different times during the treatment, the cells were subjected to different periods of treatment. The purpose of having to test and extract samples at various times during the treatment process is to study the soil property changes with respect to time. The pictorial view of the setup is shown in Figure 2. The electrodes were two 400 mm x 196 mm x 2 mm thick copper plates placed at either end of the cells for Series 1. For Series 2, four EVD of 100 mm width were arranged in a line to form an electrode plate of 400 mm width at either end. Within the cells the electrodes were separated by a distance of 400 mm.

2.2 Soil sample

The soil sample used for this study was from Singapore Lower Marine Clay whose relevant properties are shown in Table 1. To obtain better homogeneity, the soil was mixed with distilled water to reach slurry state at about 1.5 times the liquid limit prior to placing in the respective EO cells. To minimize air voids in the clay samples, the EO cells were filled with distilled water before the clay slurry was placed in the cells. The clay sample was then consolidated to 20 kPa overburden pressure using dead weights or hydraulic jack. Settlement readings were taken continuously as to determine the time for 90% consolidation. The EO treatment commenced after achieving 90% degree consolidation.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Electrode type</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>Plasticity index (%)</th>
<th>Clay content</th>
<th>Soil Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Copper</td>
<td>70</td>
<td>31</td>
<td>39</td>
<td>≈ 66 %</td>
<td>Clay of very high plasticity</td>
</tr>
<tr>
<td>2</td>
<td>EVD</td>
<td>69</td>
<td>31</td>
<td>38</td>
<td>≈ 66 %</td>
<td>Clay of very high plasticity</td>
</tr>
</tbody>
</table>

2.3 Test scheme

Two series of tests were conducted, designated as Series 1 with copper electrodes and Series 2 with EVD electrodes. They were essentially the same except for the use of different electrodes. Overburden pressure of 20 kPa was maintained throughout the EO treatment process. Polarity reversal was set at 12-hour intervals. In order to examine the changes in properties with time, the small EO cells underwent treatment time of 0, 12, 36 and 72 hours whereas the EO treatment in the large cell was carried out for 72 hours only. After mechanically consolidating the soil to 20 kPa, pre-treatment testing involving water content, vane shear strength, Atterberg’s limits and consolidation tests were performed in small cell No 1 from each series. The results served as benchmark for comparing changes, if any, in soil properties before and after EO treatment.

Due to the size constraint, only current and temperature variations were monitored for the small cells using digital multimeter and thermocouple respectively. The properties monitored in the large cell were the voltage gradient across different location in the soil sample, current variations, settlement near two electrodes, and temperature at different depths at different locations.

After the various periods of treatment, vane shear strength, water content and Atterberg’s limits were determined, following BS 1377: Part 2, (1990) for soil samples taken from each cell. This paper focuses only on voltage gradient, current variation, vane shear strength, water content and energy consumption.
Figure 1: Schematic plan view of large EO cell.

Figure 2: Pictorial view of 400 mm (L) x 400 mm (W) x 450 mm (H) EO cell.
3. TEST RESULTS AND DISCUSSION

3.1 Current variation with time

Figure 3 shows the typical trend of current variation with time for both Series 1 and 2. It can be seen that the current was ranging from 5.5 to 5.7 A and 2.95 to 3.5 A for Series 1 (copper electrodes) and Series 2 (EVD electrodes) respectively during the 1st cycle when electricity was switched on. With polarity reversal at 12-hour intervals, the current in Series 1 (copper electrodes) surged to a fairly high value of about 4 A at the start but dropped rapidly to about half the initial value in about 2 hours. Similar trend was observed in Series 2 (EVD electrodes) with a smaller magnitude and within a shorter time. Six cycles of polarity reversal were performed and it can be seen that the odd numbered cycles exhibited the same trend as the 1st cycle (referred hereinafter as Cycle A) while the even numbered cycles followed the trend of 2nd cycle (referred hereinafter as Cycle B). This happened for both Series 1 and 2 which suggest that both the copper and EVD electrodes have the same current characteristic during EO treatment though Series 2 had a smaller current magnitude.

3.2 Voltage gradient

For the ease of discussion, electrodes are referred to as P or Q depending on their role as anode and cathode respectively in Cycle A (in the first cycle) of polarity reversal. In situ electric potential in clay measured with voltage probes at different locations in Cycles 1 for both series are shown in Figure 4 and 5. Some potential losses at the soil-electrode contact were readily apparent. This means that not all the potential gradient applied were transferred to the soil. It can also be seen that the effective voltage gradient in soil decreased with time. This implies that the EO efficiency drops with time. Hamed and Bhadra (1997) reported similar observations. Bjerrum et al. (1967) and Lo et al. (1991) also reported the same trend in their field applications. The similar trend can be observed on all the cycles in both series. It is interesting to note that the electrical potential at the EVD electrodes itself has showed some drop as compared to the total applied voltages. This is in contrast with the copper electrodes which showed no drop. Due to this reason, the effective voltage gradient across the electrodes is smaller in Series 2 as can be seen from the gentler gradient in the middle portion in Figure 5 as compared to Figure 4. This probably explains why the magnitude of current is lower in Series 2 as compared to Series 1.

Figure 3: Current variation with time for copper and EVD electrodes.
Figure 4: Normalized voltage between P (Anode) and Q (Cathode) during 1st cycle (0-12\textsuperscript{th} hour) of Series 1 with copper electrodes.

Figure 5: Normalized voltage between P (Anode) and Q (Cathode) during 1st cycle (0-12\textsuperscript{th} hour) of Series 2 with EVD electrodes.
3.3 Undrained shear strength and water content

The undrained shear strength and water content profile with time are shown in Figures 6 and 7 for Series 1 and 2 respectively. It can be seen that larger increment of shear strength occurred at regions near the electrodes with relatively small increment at the middle of the cell. This is consistent with the variation of water content where regions near the electrodes exhibit larger reduction in water content. Both Series 1 and 2 showed similar trend and profile in strength and water content distribution though Series 2 exhibits a smaller magnitude in both parameters. This is not unexpected as Series 2 shows smaller magnitude in both current and voltage variation as discussed earlier. The smaller current transmitted between electrodes in Series 2 implies less ions movement and thus less of water molecules being dragged to the electrodes per unit time. As such, the water content remained relatively high in Series 2 and resulted in lower undrained shear strength, which is also a function of water content. The extent of electrochemical corrosion of copper electrodes is considered to be small whereas the EVD has virtually no such corrosion.

3.4 Energy consumption

The improvement in the soil in terms of undrained shear strength gain and water content reduction was much more significant in Series 1. In addition, there were larger voltage losses incurred due to the relatively higher resistance of polymer, resulting in lower current deployment and less effective electrical potential being transferred in Series 2. It is to be noted that the total energy consumed by Series 1 is about 200% more than that in Series 2. This is calculated based on the applied constant voltage and the area under the current variation during tests. Hence, it is not surprising that Series 1 shows better improvement than Series 2.

A more meaningful comparison is made by using the average increase in shear strength normalized by the energy supplied per unit volume of soil treated. Although the undrained shear strength increment is not entirely uniform across the sample, this method nevertheless gives some indication on the relative performance of the two types of electrodes involved. Figure 8 shows the relative efficiency of copper and EVD electrodes. It can be seen that the incremental difference in undrained shear strength between the two tests reduced from 0.18 kPa/(kWh/m³) at 12th hours to 0.07 kPa/(kWh/m³) at 72nd hours. The difference narrowed as treatment continued. This may mean that more time is needed for EVD electrodes to achieve the same strength gain in comparison to copper electrodes. However, EVD offers other advantages such as the resistance to electrochemical corrosion with time. Hence, if other practical considerations such as ease of installation and material costs are taken into account, EVD can still be a viable cost effective alternative to copper electrodes in EO operation.

4 CONCLUSIONS

In general, it can be seen that the EO process with EVD electrodes exhibited the same trend as copper electrodes in terms of current variation, improvement of undrained shear strength with time and corresponding reduction in water content, with values consistently lower than that of copper. This shows that EVD has the same characteristic as copper electrodes in EO operation, except with slightly higher electrodes resistance.

Considerable amount of electrical potential energy applied to the electrodes is lost at the soil-electrode contacts for both copper and EVD electrodes. Greater losses were incurred with EVD. A large voltage was needed to overcome the high resistance of the polymer as compared to copper. The effect of this loss is apparent in the smaller gain in undrained shear strength and smaller reduction in the water content.

The electrical efficiency of the electrodes is assessed by the increase in undrained shear strength normalized by the electric energy supplied per unit volume of treated soil. It was found that the efficiency of EVD was lower by about 50% compared to that of the copper. Hence, longer time and more energy are needed to achieve the same strength increment as copper electrodes. As compared to conventional PVDs with surcharge, using EVD for EO treatment may still be a faster and a cost effective alternative. This is due to the shorter consolidation time. Moreover, surcharge application and removal may not be needed in this case, that will result in further cost saving over conventional PVD treatment. EVD can be further enhanced with the improvement in its conductivity using the latest polymer technology.
Figure 6: Undrained shear strength and water content profile with time for Series 1 (copper electrodes).

Figure 7: Undrained shear strength and water content profile with time for Series 2 (EVD electrodes).
Figure 8: Efficiency in terms of increase in shear strength per unit energy consumed per unit volume of treated soil.

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REFERENCE


