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Electro-osmotic consolidation of soft clay based on laboratory and field trials

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ABSTRACT: Laboratory and field investigation into the effects of electro-osmotic consolidation process on soft clay is reported in this paper. Properties of soft clay are investigated using small diameter cylindrical specimens as well as large diameter samples with electrically conducting vertical drains. Instrumentation has revealed the pore pressure behaviour, settlement of the clay and the undrained shear strength profile in the soft clay after EO treatment. A considerable improvement in compressibility properties is shown after EO. Chemical changes associated with the treatment are discussed. A field trial conducted with conductive polymer vertical drains in a land reclamation project in Singapore is discussed. Drains were installed at 1.2m spacing using conventional installation machines. The supply of electricity with polarity reversal has shown that undrained shear strength in soft clay can be achieved ten times faster in soft clay when compared with the normal prefabricated drains without EO application.

1 INTRODUCTION

Deposits of soft clayey soil, particularly Singapore marine clay (SMC), pose construction problems related to settlement and stability. The common soil improvement technique in this soil involves application of prefabricated vertical drains (PVD) and surcharge to eliminate primary consolidation settlement and a large proportion of secondary settlement. To reduce this waiting time further and to be less dependent on the need to place and remove surcharge, National University of Singapore (NUS) initiated work in an old science of Electro-osmosis (EO) but a relatively new area of technology. Here, electricity is passed through electrically conducting vertical polymer drains (EVD) to accelerate consolidation of SMC.

The Helmholtz and Smoluchowski Theory is the earliest and most widely used model to explain hydraulic flow under EO. By analogy with Darcy's law, the hydraulic flow of water under an electric potential gradient can be written as (Mitchell, 1991)

$$q_A = k_e\, i_e\, A \tag{1}$$

where q_A: discharge capacity under EO (m^3/s), k_e: coefficient of Electro-osmotic permeability ($m^2/s/V$), i_e: electric potential gradient (V/m), A: cross sectional area of flow (m^2).

In EO, electrodes are placed in soft soils, for passing direct current (DC) electricity. Cations are attracted to the cathode, dragging with them the free water molecules. Anions are simultaneously attracted to the anode. The net water movement is towards the cathode and if drainage is provided, consolidation occurs beginning at the anode. The usefulness of EO lies in its suitability for rapid improvement in clay rich soils. For this type of soils, EO is potentially more effective in reducing the water content than conventional PVD, which uses only hydraulic gradient created by external loading (Mitchell 1991).

Extensive research with EO has been carried out on clay soils in Canada, Germany, Norway and the UK (Hamir et al., 2001), and recently in Southeast Asian countries. Improvements in shear strength followed EO treatment of these soils. Recently, a proposal to consolidate soft marine clay utilizing the EO principle by means of Electric Vertical Drains (EVD) was accepted for trial funding by The Enterprise Challenge Unit in Singapore. The location of the trial site was at Tuas View Reclamation Project with JTC Corp acting as the Piloting Agency for the trial.

2 LABORATORY INVESTIGATIONS

2.1 *Small specimens*

In laboratory studies, one-dimensional consolidation tests were carried out with and without EO. A modified oedometer built with non-conductive acrylic material was used as a cell, and the consolidation stress was applied mechanically. Two insulated wires, soldered to horizontally placed stainless steel anode at the bottom and cathode at the top, were then connected to the DC power source.

Remolded SMC mixed to initial water content equal to its liquid limit was used to ensure uniform soil properties throughout the test series. All specimens, 20mm thick initially, were consolidated to 100 kPa in stages so as to enable comparison. Two series of specimens designated as 1A and 1B were then subjected to EO under a voltage difference of 2V and 3V respectively while specimen 1C was held as a control specimen without EO application. At the end of EO, the treated soil was subjected to further investigation. The loading was extended to further two days to examine the changes in the coefficient of secondary compression C_α. EO treated soil was tested for water content variation with depth and pH.

Figure 1 shows void ratio – pressure (e vs. log p') relationship of samples. EO treated soil lacks a well-defined sharp kink at the pre-consolidation pressure as observed by Bo et al. (2000). EO treatment shows an apparent increase in the coefficient of consolidation Cv, and apparent decrease in compression index Cc and coefficient of secondary compression C_α determined in a two-day test period. For loading above 300 kPa, Cv became stabilized, with Test 1A having an average increase of about 40% and Test 1B a 200%. A decrease in C_α of EO treated clay amounted to 10% to 30% in the stress range up to 800 kPa (Toh et al. 2001).

2.2 *Large specimens*

The feasibility of applying EO to Singapore marine clay was also investigated in moderately large diameter cylindrical samples, 500mm diameter and 150 mm thick. A particular aspect of this study centred on the type and spacing of vertical drains and other field implications (Lim, 2001). Figure 2 shows the plan and cross sectional elevation of the apparatus, where two electrodes were introduced in the clay at liquid limit. The position of electrode probes for measurement of voltage and current in the clay is shown. The sample after treatment was subject to geotechnical property investigations using oedometer and laboratory vane shear tests.

The properties of Singapore marine clay used are $W_P = 35$, $W_L = 80$, $I_P = 45$ and sand, silt and clay proportions = 2%, 46% and 44% respectively.

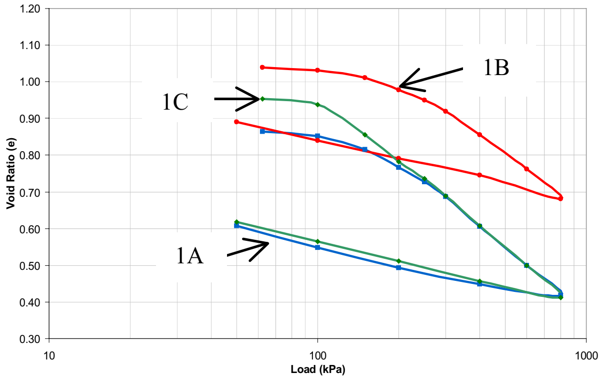

Figure 1. Void ratio vs consolidation pressure of SMC

2.3 *Test scheme*

Three electro-osmosis consolidation tests, designated as Test 1, Test 2 and Test 3, were conducted. The clay for the three tests was consolidated to 31 kPa, 52 kPa and 30 kPa respectively simulating the conditions of soft clay normally encountered in Singapore. Upon completion of 90% average degree of consolidation, as observed by settlement and pore pressure readings, the vertical pressure was removed. Undrained shear strength profiles via laboratory vane and water content profile were determined across the electrode positions. See Figure 3 for the initial shear strength.

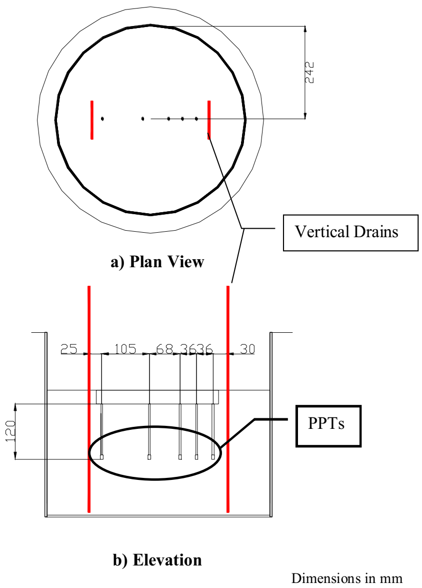

Figure 2. EVD apparatus for large diameter specimens

After establishing the initial parameters, the clay was reconsolidated to the original vertical pressure. During electro-osmosis consolidation, constant D.C. voltage of 20V was applied between the electrodes. Tests were stopped when settlement was observed to have petered out and pore pressure readings have stabilized.

2.4 *Test results*

The profiles of shear strength after electro-osmotic consolidation, shown in Figure 3 for Test 1, are similar to those reported by Abiera et al. (1999) and Bergado et al. (2000). The soil near the anode had the largest increase in undrained shear strength followed by the soil at the cathode. Undrained shear strength in the mid-section had minimal strength increase. Figure 4 shows the percentage increase in undrained strength between the electrodes in Tests 1, 2 and 3. Figure 5 shows the profiles of percentage decrease in water content. The decrease was lowest in the mid-section and highest near the electrodes, similar to reported laboratory test results by Abiera et al. (1999) and Bergado et al. (2000). These water content profiles correlated well with the undrained strength profiles.

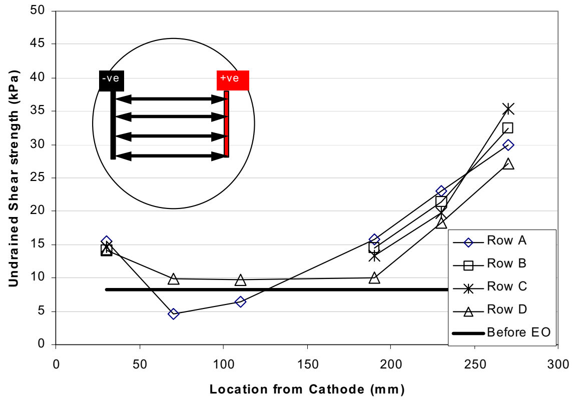

Figure 3. Undrained shear strength after EO

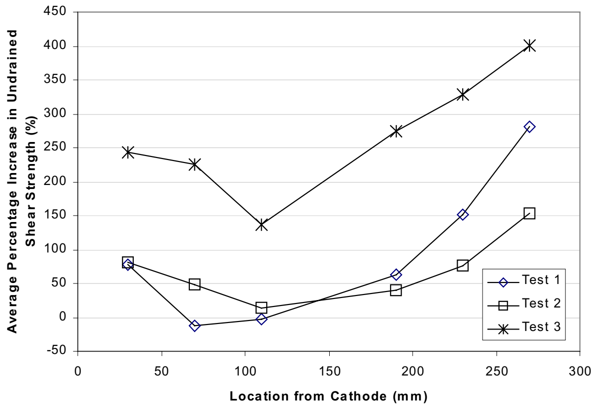

Figure 4. Percentage change in undrained shear strength

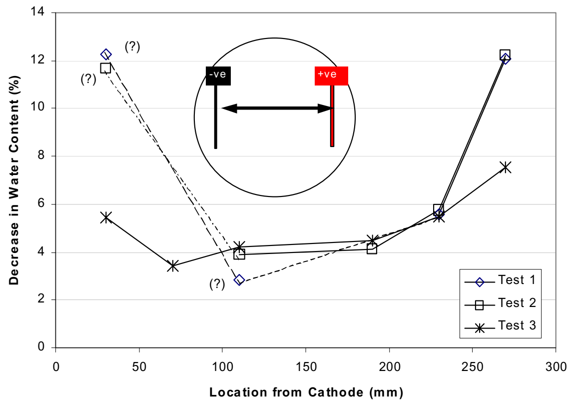

Figure 5. Percentage change in water content

There was a large undrained shear strength increase in Test 1, which had higher initial water content, than in Test 2, especially near the cathode. It is observed that there is a greater percentage improvement in softer clay (Test 1) by electro-osmosis than in stiffer clay (Test 2) as also observed in Lo et al. (1991). This clearly showed that electro-osmosis is more efficient in softer clay than stiffer clay.

Figure 6 shows the variation in the pore pressure within the clay between the electrodes, the larger variation being associated with the proximity to the anode. Shang (1998) also observed reduction of pore pressure at the anodes.

Other phenomena observed are (1) current initially rose, became stable and then dropped, (2) gas evolved at electrodes, (3) settlement continued to occur following nearly the trend shown by the current (4) samples strained between 3.3% to 5.6%, (5) pH rose to about 14 initially at the cathode and decreased to about 12, at discharge and (6) electrical energy used up varied from about 14 to 28 kWh / m^3.

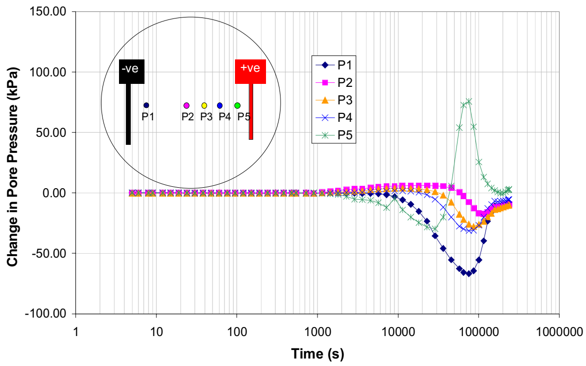

Figure 6. Pore pressure variation between electrodes

2.5 *Compressibility of soil*

Figures 7 shows the void ratio – consolidation pressure (e vs log p') of the marine clay after EO treatment for Test 1. There are significant changes in compressibility characteristics, such as Cc decreasing from about 0.67 to about 0.43, 0.45 and 0.57, and Cr from 0.17 to 0.13, 0.14 and 0.15 for the Tests 1, 2 and 3 respectively. The percentage increase in pre-consolidation pressure based on the assumption of a virgin compression curve with Cc = 0.67 ranged from 21% to 173% for the same three Tests. There is, therefore, a tendency for the EO treated clay to have reduced compressibility, which would reflect in the field as observed settlement of smaller magnitude under the same applied pressure.

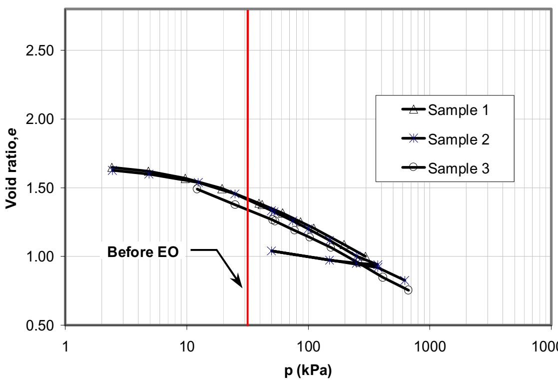

Figure 7. Void ratio vs pressure after EO

3 FIELD TRIAL

A field trial was conducted in 2001 in Singapore to examine the feasibility of EO in consolidation of soft clay. The trial consisted of installing and electrifying two plots of land with a patented electrically conductive plastic vertical drain known as EVD. The site under the jurisdiction of the JTC Corp. was at Tuas View Reclamation Phase IV, Singapore, in the western part of Singapore island.

In a plot of 50m by 50m, underlain by 18.7m of sand fill and 8 m of soft marine clay, anode and cathode drains, all having filter sleeves, were installed on a 1.2m square grid using a standard PVD installation rig with no special equipment or modification. Figure 8 illustrates the installed EVD after wiring. There were four sub-plots to investigate various EVD configurations. Each sub-plot had a piezometer and a deep settlement gauge located approximately at the centre. After EO treatment, insitu vane shear tests were carried out in the soft clay. Only subplot 2A results are discussed in this paper.

Figure 8. EVD installed with conventional PVD machines and wired

3.1 *Pore pressure*

Within 7 hours of electricity application through EVD, pore pressure reading in P5 surged approximately 3kPa. When polarity was reversed 24 hours later, pore pressure reading surged 14kPa within 3 hours. Subsequent polarity reversals caused similar surge in pore pressure readings but with decreasing magnitude. There was a significant drop in excess pore pressure between 28th Jun 2001 and 30th Jun 2001. Continued electricity application and reversed polarity did not create further changes to pore pressure readings. Figure 9 shows pore pressure readings in (P5) Sub-plot 2A and in (P3) nearby untreated section.

The readings indicated that significant pore water pressure changes had occurred when electricity was applied. However, direction of pore water movement could not be inferred from the single piezometer. In addition, pore pressure was not lowered as expected in electro-osmosis, but increased instead. Increase in pore pressure was expected in the initial stages of electro-osmosis.

3.2 *Field Vane Shear Test*

From the electrical and pore pressure readings and also taking into consideration the dateline for this trial, it was judged that further electricity application would not cause additional changes to the readings in Sub-plot 2A. Hence, electricity was terminated on Day 13, and Field Vane Shear test was promptly conducted in Sub-plot 2A and in an untreated section of Plot 2. The results of the Field Vane Shear test and percentage change in undrained shear strength, as shown in Figure 10 indicate a large shear strength increase especially in the upper half of clay layer in Sub

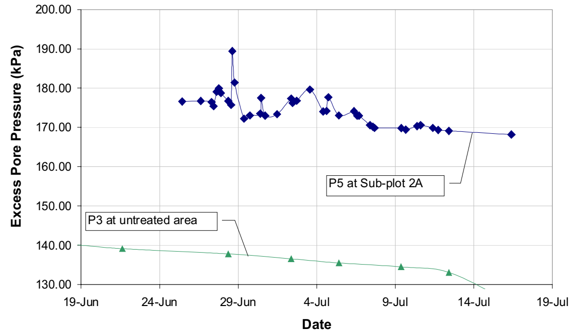

Figure 9. Pore pressure variation in sub-plot 2A on EO application

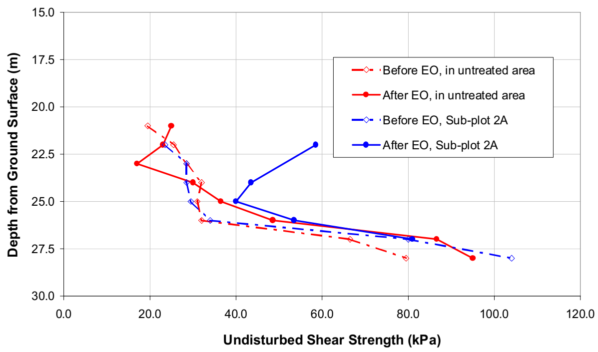

Figure 10. Field vane shear strength profiles at various stages of treatment

-plot 2A. The increase in Sub-plot 2A below 27.0m is affected by the closer proximity to stiff clayey silt, which has lower water content. In addition, the massive amount of overburden pressure from 18.7m of reclamation sand fill on the soft clay may have a slight "depth effect" as suggested by Lo et al. (1991).

The substantial difference between EO treated and untreated clay indicates that electro-osmosis caused greater improvement in the shear strength than conventional treatment by PVD action.

The increase in undrained shear strength of soft marine clay with consolidation for Singapore Marine clay follows a Cu/Po' of 0.26 to 0.28. If EVD were to perform as a hydraulic PVD installed at the same 1.2m spacing, the undrained shear strength would increase with time as shown with the broken line in Figure 11. The vane shear strength before and after EO treatment yielded a Cu variation as shown by the solid curve, which was achieved in 13 days. The time taken by the PVD for the equivalent gain n strength would have been about 130 days illustrating a ten-fold reduction in time to achieve the same strength in soft marine clay.

4 CONCLUSIONS

The review of laboratory and field data presented in this paper leads to the following conclusions:

1) EO treatment causes substantial reduction in Cc and Cr in soft (SMC) clay and increase in Pc. Tendency of Cv to increase is mainly due to the reduction in soil compressibility. These soil characteristics point to reduced settlement after treatment in comparison with the untreated clay.
2) Pore pressure behavior is more prominent at the anode where reduction is more apparent with the progress of EO. This aspect is conducive to monitoring of field execution of EO.
3) Increase in undrained shear strength is observed in EO treated soft clay, more conspicuously at the anode than at the centre or near the cathode.
4) Chemical changes depicted by soil stains and substantial change in pH may provide the clue for increase in shear strength and drop in compressibility properties.
5) Field observations illustrate that the undrained shear strength increases after a few days of EO application with reversed polarity. A tenfold reduction in time was observed in a field trial involving conductive polymeric vertical drains installed in soft clay at 1.2m spacing.

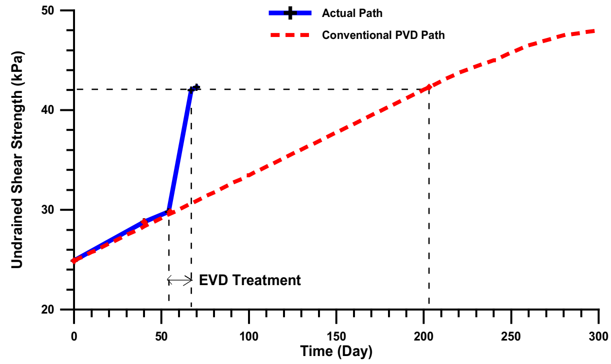

Figure 11. Undrained shear strength variation with PVD and EVD

5 ACKNOWLEDGEMENT

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