Research Article

Electrokinetic Treatment for Model Caissons with Increasing Dimensions

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1. Introduction

Soft soils and marine deposits are very common around the world. There are many infrastructure projects and coastal high-rise buildings whose foundations are often supported by such soils of low shear strength and high compressibility. Furthermore, exploration and development of oil and gas fields around the world and expansion of wind farms has resulted in the construction of many platforms and towers on offshore soils with low shear strength. The construction of these projects on soft soils can lead to very expensive foundation systems. Moreover, the installation of traditional foundation elements, particularly driven piles or caissons, can destroy any naturally existing cohesion or cementation between the soil particles and disturb the structure of the soil in the close vicinity of the foundation, causing excessive settlement and further reduction in the foundation’s loading capacity.

Electrokinetic treatment is an effective soil improvement technique to increase shear strength and load capacity of foundation elements in soft soils. Electrokinetics improves the strength properties of soft soils by inducing electrokinetic consolidation (e.g., [1]), generating electrokinetic cementation (e.g., [2]) and reducing the water content (e.g., [3]). Major benefits of using electrokinetic treatment are the limited disturbance the treatment may cause to the existing soil structure and the ability to control the zone of treatment. Electrokinetic treatment has been known in geotechnical engineering for over six decades [4, 5] with successful laboratory scale investigations (e.g., [6, 7]) and field experimentations (e.g., [8–10]). Furthermore, case records are reported where electrokinetics was successfully used to improve the load capacity of a friction pile [11] and control the pore water during excavation [12]. However, the technique is in fact seldom used on a professionally recognized scale. The reluctance of the ground improvement
A critical issue that needs to be investigated and understood in order to devise design guidelines for electrokinetic treatment systems from experimental results is the effect of the foundation element size on the gained improvement. Equally important for the guideline is determining the optimum distance between the anode(s) and the cathode(s). Optimum electrode spacing focuses the electric field in the vicinity of the foundation element and controls the size of the treatment zone. Thus, the improvement in the strength properties of the soil occurs in foundation-soil interface with the lowest energy consumption. Finally, estimating the power consumption prior to an electrokinetic treatment is critical to evaluate the economic viability of the treatment. These are major issues that need to be investigated and understood in order to extrapolate, correlate, and/or model the results from bench-scale, laboratory-floor, and pilot tests for full-scale applications.

This experimental study is a preliminary step to address some of the issues important for devising guidelines for electrokinetic treatment. The study investigated the axial load capacity of model caissons with increasing dimensions embedded in soft soil under water after electrokinetic treatment. The study attempted to correlate the load capacity and energy consumption to the surface area of the model. The study proposed a formula for the distance between the electrodes.

2. Experimental Program

2.1. Material Properties. The soil used in this study was recovered from a construction site in Thunder Bay, ON. Grain size distribution analysis on the soil was performed in accordance with ASTM D422-63 [13] and showed that 15.5% of the soil is sand size and 84.5% is fines (silt and clay). The liquid and plastic limits of the soil, determined by ASTM D4318-10 [14], are 25 and 19, respectively. The Unified Soil
Classification System group symbol of the soil is CL-ML and the group name is silty clay with sand. The natural water content of the soil was 36% and the specific gravity is 2.72.

2.2. Experimental Setup and Procedure. Three identical electrokinetic treatment cells were designed and manufactured for the study. The cell, shown in Figure 1, was made from polyvinyl chloride (PVC) pipe 320 mm in outside diameter, 300 mm in inside diameter, 650 mm in length and with a volume capacity of 45 litres. One side of the pipe was covered with a PVC cap that served as a base for the cell. A drainage valve was installed at the base of the cell to facilitate saturation.

Four model caissons with 3 mm wall thickness and increasing diameters and lengths were manufactured from steel and used in the experiments. The surface area was doubled each time from the smallest to the largest model caisson. The outside diameter and length of the model caissons were 50 mm and 102 mm in test 1, 75 mm and 136 mm in test 2, 100 mm and 204 mm in test 3, and 150 mm and 272 in test 4. The corresponding surface areas (SAs) were 16000, 32000, 64000, and 128000 mm², respectively. The tests are summarized in Table 1.

A mass of the silty clay soil was placed in a concrete mixture drum. The volume of water required to increase the water content of the soil to 50% was measured and added to the drum. The soil and water were thoroughly mixed in the drum in order to produce a homogenous soft soil. The water content of the mixture was selected twice the liquid limit in order to produce a soil specimen with properties of reconstituted clay as described by Burland [15] and with virtually no shear strength.

Approximately 25 mm layer of clean gravel, 5–7 mm grain size diameter, was placed at the bottom of the cell as a drainage layer, which was overlain by a geotextile filter (Figure 1(a)). The soft clayey soil was then poured into the cell. The soft soil was allowed to settle and consolidate over its own weight for 48 hr. After settlement and consolidation, the soil specimen was approximately 465 mm high (150 mm shorter than the cell) and was overlain by a layer of water. The electrical conductivity of the soil, σ, was measured using ASTM G57-6 [16] and founded to be 0.1 S/m. The model caisson was then inserted into the cell with the centre of the caisson coinciding with that of the cell. The upper of the model caisson was 50 mm below the soil specimen as shown in Figure 1(a). The model caisson served as the anode during the treatment. Four electrodes serving as the cathode were inserted around the model caisson at equal distance from each other. The electrode was made of perforated steel pipe, 12 mm outside diameter, 8 mm inside diameter and was 25 mm longer than the model caisson. The perforation holes were 3 mm in diameter at spacing of 13 mm centre-to-centre. The tops of the electrode and the model caisson were at the same level while the tip of the electrode was 25 mm below the base of the caisson (Figure 1(a)).

The electric field was simulated for various distances between the anode (model caisson) and the cathode (four electrodes) by using QuickField [17], a field simulation software. The simulation aimed to provide the maximum electric field, and subsequently the maximum improvement in the strength properties of the soil, in the caisson-soil interface. A distance equal 0.25 times the outside diameter of the model caisson was identified as optimum for electric field between the caisson and cathode. Thus, 13, 19, 25, and 38 mm were the distances between electrode and model caisson in tests 1 to 4, respectively. The plan view of the electrodes layout in test 3 is shown in Figure 1(b). After installing the model caisson and the electrodes, the water above the soil specimen was raised to 100 mm and kept throughout the duration of the treatment and the shear strength and axial load tests.

A direct current (dc) voltage of 6 V was applied to the cell with the model caisson serving as the anode and four electrodes (A1 to A4) serving as the cathode. The electrokinetic treatment lasted for 168 hr with current intermittence intervals of 2 min on and 2 min off executed by a programmable timer. Current intermittence, the application of a pulse voltage at predetermined on/off intervals instead of a continuous dc voltage, was selected for its superior outcome in electrokinetic treatment as well as its effectiveness in reducing corrosion of the electrodes [7, 18, 19]. The electric current was monitored and reported during the treatment. For each electrokinetic treatment test in this study, a control test with identical soil and configuration but without electric field was carried out to provide baseline data for comparison.

3. Results and Discussion

3.1. Electric Field and Energy Consumption. Figure 2 shows the electric current across the tank versus the elapsed time of the test. The figure shows that for the same applied voltage, the electric current increases with the increase in the surface area of the model caisson. This is due to the
**Figure 3:** (a) Plan view of electric field intensity, $E$ (V/m), distribution in the cell; (b) $E$ along cross-section B-B of the cell; (c) $E$ along cross-section C-C of the cell.

**Figure 4:** Energy consumption, $Q$, versus surface area, $SA$, of the model caisson.
Table 1: Summary of tests and results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Model caisson</th>
<th>Energy consumption</th>
<th>Displacement at failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dia. mm</td>
<td>Length mm</td>
<td>SA mm²</td>
</tr>
<tr>
<td>Test 1</td>
<td>50</td>
<td>102</td>
<td>16000</td>
</tr>
<tr>
<td>Test 2</td>
<td>75</td>
<td>136</td>
<td>32000</td>
</tr>
<tr>
<td>Test 3</td>
<td>100</td>
<td>204</td>
<td>64000</td>
</tr>
<tr>
<td>Test 4</td>
<td>150</td>
<td>272</td>
<td>128000</td>
</tr>
</tbody>
</table>

EK: electrokinetic.

Figure 5: Undrained shear strength, \( s_u \), versus distance from the centre of model caisson.

Increase in the soil area subject to the electric current as the caisson increases. The electric current values shown in Figure 2 represent the integration of the current density over the soil area subjected to the current. As the surface area of the caisson increases, the area in the soil subjected to the current increases and so does the current.

Figure 2 shows electric current in tests 1 and 2 decreased throughout the test with the sharpest decrease occurring during the first 20 hr. In test 3, the current increased with time during the first 40 hr of the test. After, the current decreased slightly with time up to the end of the test. In test 4, the current slightly deceased during the first 20 hr of the test and then increased. The current then decreased with small rate until the end of the test. The change in electric current with time as shown in Figure 2 resulted from the change in electrical conductivity of the soil during the test. The change in the conductivity of soil during an electrokinetic process is a result of two opposing mechanisms. In general, as the pore
fluid drained out of the soil mass (pore fluid dominates the bulk conductivity of the soil) by electroosmosis, the bulk electrical conductivity of the soil decreases. However, for water still remaining inside the soil pores, the electrical conductivity increases with the treatment time as a result of electrolytic reactions associated with the electrokinetic process [20, 21]. Therefore, the increase in the electrical conductivity of the pore fluid by the electrolytic reactions can sometimes become more dominant than the decrease in conductivity of the soil resulting from the draining of water. Thus the bulk conductivity of the soil, and thereby the electric current, may start to increase sometime after the start of the electrokinetic treatment as observed in tests 3 and 4. However, Figure 2 suggests that for all tests, the change in current and thereby the change in electrical conductivity was very small during most of the testing time.

Figure 3(a) shows distribution of the electric field intensity, $E$, during test 3 simulated using QuickField. The $E$ distribution shown in Figure 3(a) was typical in all the tests. Figures 3(b) and 3(c) show plan views of $E$ across the centre of the cell and two electrodes (section B-B) and across the centre of the cell and midway between electrodes (section C-C) for test 3. As shown in the figures, the highest $E$, and subsequently the highest current density (current density = $Ea$), occurred in the vicinity of the caisson. In test 3, $E$ varied between 112 and 210 V/m (i.e., current density between 11.2 and 21 A/m$^2$) in the model caisson-soil interface compared to $E$ and current density of zero in the soil near the wall of the cell.

The energy consumption, $Q$, during electrokinetic treatment was calculated for each test and is shown in Figure 4 versus the surface area (SA) of the model caisson. As shown in the figures, $Q$ increased linearly with SA as

$$Q \text{ (Whr)} = 108 \times 10^{-5} \text{ SA (mm}^2\text{)} + 16 \quad (1)$$

Thus, for soil with electrical conductivity of 0.1 S/m, applied voltage of 6 V, and electrodes layout similar to the configuration in this study, the energy consumptions per week of treatment can be estimated by (1).

3.2. Undrained Shear Strength. After the completion of the electrokinetic treatment, the undrained shear strength, $s_u$, was measured in three locations shown in Figure 1(b) (SL1, SL2, and SL3) using a shear vane. At each location $s_u$ was measured at the top, mid, and bottom levels of the model caisson. An average value for $s_u$ was determined from the three measurements for each location and presented in Figure 5. After the treatment, the average $s_u$ varied between $14 \pm 1.3$ kPa and $17 \pm 1.5$ kPa in the model caisson-soil interface (SL2) and between $1.6 \pm 0.2$ kPa and $4.1 \pm 0.5$ kPa at 130 mm from the centre of the caisson (SL2). The corresponding $s_u$ in the control tests ranged from $1 \pm 0.1$ kPa to $2.6 \pm 0.2$ kPa. The relationship between the magnitude of the electric field (stronger in the vicinity of the model caisson and weaker away from the caisson) and gained strength in the soil are illustrated for test 3 by Figures 3(b) and 5. At SL2, $201 \text{V/m} \geq E \geq 112 \text{V/m}$ and $s_u = 15 \pm 1.3$ kPa whereas at SL3, $E \leq 7 \text{V/m}$ and $s_u \leq 2.8 \pm 0.3$ kPa. Thus focusing the electric field near the caisson significantly increased $s_u$ in the caisson-soil interface as, a primary objective of the optimizing the distance between the electrodes while $s_u$ away from the caisson remained approximately similar to that of the control.

As shown in Figure 5, the treatment also increased the strength of the soil inside the model caisson (SL1) with the highest shear strength reported in tests 1 and 2. The higher strength in tests 1 and 2 was likely due to the smaller size of the model caissons in the two tests. As the size of the model caisson decreased, more water was drained by electroosmosis out of the enclosed soil since the caisson was serving as an anode. Increasing shear strength for soil inside a foundation element can generate a soil plug. For caisson foundations, a soil plug adds a toe bearing resistance component and thereby increases the axial load capacity.

3.3. Axial Load Capacity. After measuring $s_u$, the model caisson was axially loaded to failure by a triaxial load frame as shown in Figure 6. Figure 7 shows the axial load capacity, $P$, versus the vertical displacement of the model caisson after the electrokinetic treatment and for the control tests. The axial load capacity at failure, $P_f$, is marked on the figure. $P_f$ was determined by the failure criterion proposed by Tani and Craig [22]. In this failure criterion, the failure was at the point of intersection of the load-displacement curve and the bisector line of the angle made by two tangents on both sides of the sharp bend of the load-displacement curve. As shown in Figure 7, $P_f$ after electrokinetic treatment was 126 N in test 1 (SA = 16000 mm$^2$), 205 N in test 2 (SA = 32000 mm$^2$), 327 N in test 3 (SA = 64000 mm$^2$), and 521 N
in test 4 (SA = 128000 mm²). The corresponding $P_f$ values in the control tests were 12, 45, 84, and 170 N, respectively. This represents an increase between 206 and 950% after electrokinetic treatment as compared to the control.

Figure 8 shows $P_f$ (N) versus the surface area, SA (mm²) of the model caisson for the four tests. As shown in the figure, $P_f$ varied linearly with SA for the range covered in this study and the relationship is given by:

Control tests:

$$P_f (N) = 1373 \times 10^{-6} \text{SA (mm}^2\text{)} - 4.$$  \hspace{1cm} (2)

Electrokinetic treatment tests:

$$P_f (N) = 3458 \times 10^{-6} \text{SA (mm}^2\text{)} + 87.$$  \hspace{1cm} (3)

A linear relationship between $P_f$ and SA is expected in the control tests as the commonly used formulas for the axial load capacity are linear function between the soil properties and the dimensions of the foundation elements. A linear relationship between $P_f$ and SA after an electrokinetic

**Figure 7:** Axial load capacity, $P$, versus vertical displacement of the model caisson.

**Figure 8:** Axial load capacity at failure, $P_f$, versus surface area, SA, of the model caisson.
treatment means that the improvement in the strength properties of the soil after the treatment is independent caisson foundation dimensions. This is very important as it allows a preliminary estimation of the axial capacity for full-scale foundation element from laboratory testing of much smaller models. For example, $P_f$ for a caisson foundation with a diameter of 1 m and a length of 8 m (SA $= 25 \text{ m}^2$) inserted in soil with geotechnical properties similar to the silty clay used in this study and under water can be estimated from (2) as 34 kN. However, after an electrokinetic treatment with electric field configuration similar to the configuration in this study, $P_f$ is estimated by (3) as 87 kN and the corresponding energy consumption from (1) is 27 kWhr.

4. Conclusions

This experimental study aimed to investigate some parameters that are critical for devising design guidelines for electrokinetic treatment. Four model caisson with surface areas between 16000 and 128000 mm$^2$ were embedded in soft clayey soil under water and treated with a dc voltage of 6 V for 168 hr. From the study we can conclude the following.

(i) The axial load capacity of the caissons after the electrokinetic treatment varied between 126 and 521 N compared to 12 to 170 N in the control tests.

(ii) A distance between the anode (model caisson) and the cathode equal 0.25 times the outside diameter of the caisson was identified as optimum.

(iii) A relationship between the surface area and the axial capacity of the caisson was presented. The equation can be used to preliminary estimate the load capacity of a full-scale foundation element after an electrokinetic treatment.

(iv) A correlation between the surface area of the caisson and the energy consumption was presented. The correlation can approximately predict the energy consumption for full-scale applications prior to treatment.

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