Electrokinetic treatment: influence of energy consumption on axial load capacity

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ABSTRACT
An experimental study was carried out to investigate the effect of energy consumption on the axial load capacity of a foundation model embedded in soft clay. The tests were carried out in four identical electrokinetic treatment cells and dc voltages between 5 and 20 V with intermittent and continuous current. The results showed that electrokinetics had significantly increased the axial load capacity of the model and the increases were proportional to the energy consumption. In tests with the same energy consumption and different voltages, the increases in the load capacity were found to be similar. The maximum axial load capacity after the treatment was 336 N compared to 19 N in the control test.

RÉSUMÉ
Une étude expérimentale a été réalisée pour étudier l'effet de la consommation d'énergie sur la capacité de charge axiale d'un modèle de fondation dans l'argile molle. Les tests ont été effectués dans quatre cellules identiques traitement électrocinétique et tensions continues entre 5 et 20 V avec un courant intermittent et continu. Les résultats montrent que électrocinétique a considérablement augmenté la capacité de charge axiale du modèle et les augmentations ont été proportionnelles à la consommation d'énergie. Dans des essais sur la consommation d'énergie et même des tensions différentes, l'augmentation de la capacité de charge ont été jugés similaires. La capacité de charge axiale maximale après le traitement était de 336 N par rapport à 19 N dans le test de contrôle.

1 INTRODCUTION

Soft soils and marine deposits are very common around the world with many infrastructure projects whose foundations are often supported by such soils of low shear strength and high compressibility. The construction of these projects on soft soils can lead to a very expensive foundation system. Moreover, the installation of traditional foundation elements, particularly driven piles or caissons, can destroy any naturally existing cohesion between the soil particles and disturb the structure of the soil in the close vicinity of the foundation. Thus, causing excessive settlement and further reduction in the foundation's loading capacity.

Electrokinetic treatment is an effective and can be economically viable soil improvement technique that can be used to improve the geotechnical properties and increase the load capacity of foundations in soft soils, with minimum disturbance to the soil structure. Electrokinetics improves the strength properties of soils by inducing electrokinetic consolidation, generating electrokinetic cementation and reducing the water content. The maximum negative porewater pressure, u_e (x) (kPa), that can be developed by electrokinetic consolidation is given by (Esrig, 1968):

$$u_e(x) = -(k_e/k_h)\,\gamma_w\,E\,x = \Delta\sigma' \quad [1]$$

where k_e ($m^2/(sV)$) is the electroosmotic permeability, k_h (m/s) is the hydraulic conductivity, γ_w (kN/m^3) is the unit weight of water, E (V/m) is the electric field intensity across the soil, x (m) is the horizontal distance from the anode, and $\Delta\sigma'$ (kPa) is the increase in the effective stress.

In electrokinetic process, electrode reactions primarily control electrokinetic cementation. For example, in an electrokinetic treatment system with steel anode, the anode releases ferrous ions (Fe^{2+}) as the electrode is corroded by:

$$Fe(s) - 2e^- \rightarrow Fe^{2+}(aq) \quad [2]$$

Further oxidation changes the ferrous ions to ferric ions (Fe^{3+}), i.e.

$$Fe^{2+}(aq) - e^- \rightarrow Fe^{3+}(aq) \quad [3]$$

The ferrous and the ferric ions combined with oxygen to form Fe_2O_3 and Fe_3O_4. The formed iron oxides (natural cementing agents) precipitate into the soil's pores forming a cementation bonding between the soil particles.

The flow rate of water, Q_e (m^3/s), drained by an electrokinetic process from a soil mass with area A (m^2) perpendicular to the direction of flow is given by:

$$Q_e = k_e\,E\,A \quad [4]$$

In electrokinetic treatment with a constant applied voltage, U_o (V), the electric current, I (A), is function of treatment time due to the changes in the electrical conductivity of the soil-water system during treatment. The total energy consumption, P (Whr), over treatment time, T (hr), is given by:

$$P = \beta \int_0^T I U_o \, dt \quad [5]$$

where β is the intermittence factor:

$$\beta = \frac{\text{Power on time}}{\text{Power on time} + \text{Power off time}} \quad [6]$$

In this study, three test series were carried out to investigate the effect of energy consumption on the axial load capacity of a foundation model embedded in a laboratory prepared soft clay soil. Namely:

- Test series 1 investigated the increase in the axial load capacity of the foundation model as function of energy consumption using five applied voltages of 0 (control), 5, 10, 15 and 20 V with current intermittence intervals of 2 min on and 2 min off for 7 days (168 hr).
- Test series 2 investigated the increase in the axial load capacity of the model with applied voltage and energy consumption combinations similar to that of test series 1 with continuous current.
- Test series 3 investigated the axial load capacity of the model for applied voltages of 5, 10, 15, and 20 V with intermittence interval of 2 min on and 2 min off and energy consumption of 225Whr for each test.

Influences of the energy consumption and current intermittence on the corrosion of foundation model along with the changes in liquid and plastic limits of the soil after the treatment were also investigated.

2 EXPERIMENATL PROGRAM

2.1 Soil Properties

The soil used in the study was a mixture of 95% (by weight) inorganic grey clay obtained from Plainsman Clay in Medicine Hat, Alberta, and 5% bentonite (laboratory grade sodium montmorillonite). Kaolinite is the predominant clay mineral of the Plainsman Clay. The soft clay was prepared by mixing the dry clay mixture with tap water to a water content of 50% (1.25 times the liquid limit of the clay mixture). The water content value was selected higher than the liquid limit in order to produce a soil specimen with properties of reconstituted clay as described by Burland (1990) and with virtually no shear strength. Table 1 summarizes the properties of the mixed clay.

Table 1. Characteristics of the mixed clay

Characteristics	
Liquid limit	39
Plastic limit	18
Water content (%)*	50
Clay size (%)	51
Silt size (%)	49
Sand size (%)	0
Specific gravity	2.66

*water content of soil specimen at preparation

2.2 Experimental Apparatus and Testing Procedure

Four identical electrokinetic treatment cells were designed and fabricated to perform the tests of the study. The general design considerations of the cell were:

i. Vertical electrodes configuration. The vertical electrodes layout was selected for its practicality in field installation and the ease of replacing corroded electrode.
ii. Capability to apply a surcharge load to the soil specimen. The surcharge load can be used to simulate in-situ stress conditions, and to produce soil samples with various void ratios.

The electrokinetic treatment cell, constructed of clear Plexiglas plates 15 mm in thickness, has dimensions of 320×125×250 mm (L×W×H) and a total volume capacity of 10 litre. The voltage across a soil specimen during a test is monitored via four voltage probes installed along the base of the cell, as shown in Figure 1. The base of the cell is detachable to allow for easy recovery and minimum disturbance for the soil samples that to be used for subsequent parametric studies.

Five kilograms of dry clay mixture (4.75 kg kaolinite and 0.25 kg bentonite) and 2.5 litre of tap water were poured into the bowl of a heavy-duty kitchen mixer and allowed to thoroughly mix for 30 min. The soft soil was then poured into a larger pail with airtight cover. The process was repeated until enough soil for the test series at hand was prepared. The soil in the pail was then manually mixed to ensure uniformity and homogeneity before placement in the electrokinetic cell. The soil was placed into the cell in three layers. Each layer was rodded 25 times using steel rod, 16 mm in diameter and 450 mm long with a hemispherically shaped tip, to prevent the entrapment of air buckets. The water content of the soil (1.25 times the liquid limit) and the thorough rodding during placement in the cell insured that the soil specimen is nearly, if not fully, saturated. The foundation model, 130×75×3.2 mm (L×W×T), was then placed in the centre of the electrokinetic cell as shown in Figure 1. Two pipe electrodes, made of perforated steel pipe 14 mm outside diameter, 10 mm inside diameter and 150 mm long, were placed at 100 mm from the sides of the foundation model (see Figure 1). The pipe electrodes were filled with course sand to serve as vertical drains in addition to their primary role as an electrode. A geotextile filter was placed on the top of the soil specimen followed by the loading plate, as shown in Figure 1. After 24 hr of placing the model and electrodes, a surcharge load of 40.8 kg (corresponding to a pressure of 10 kPa) was applied to the soil specimen via the loading plate in four increments over a period of seven days. The first surcharge load was 5 kg, followed by 10 kg, 20 kg, and 40.8 kg, respectively. The settlement with time was monitored and reported for each load increment using the two dial gauges mounted on the loading plate. The load was increased to the next level after the primary consolidation from the previous load increment approached completion as indicated by the settlement-time curve. After the completion of the primary consolidation (7 days after the first load was applied), the electric field was switched-on for electrokinetic treatment.

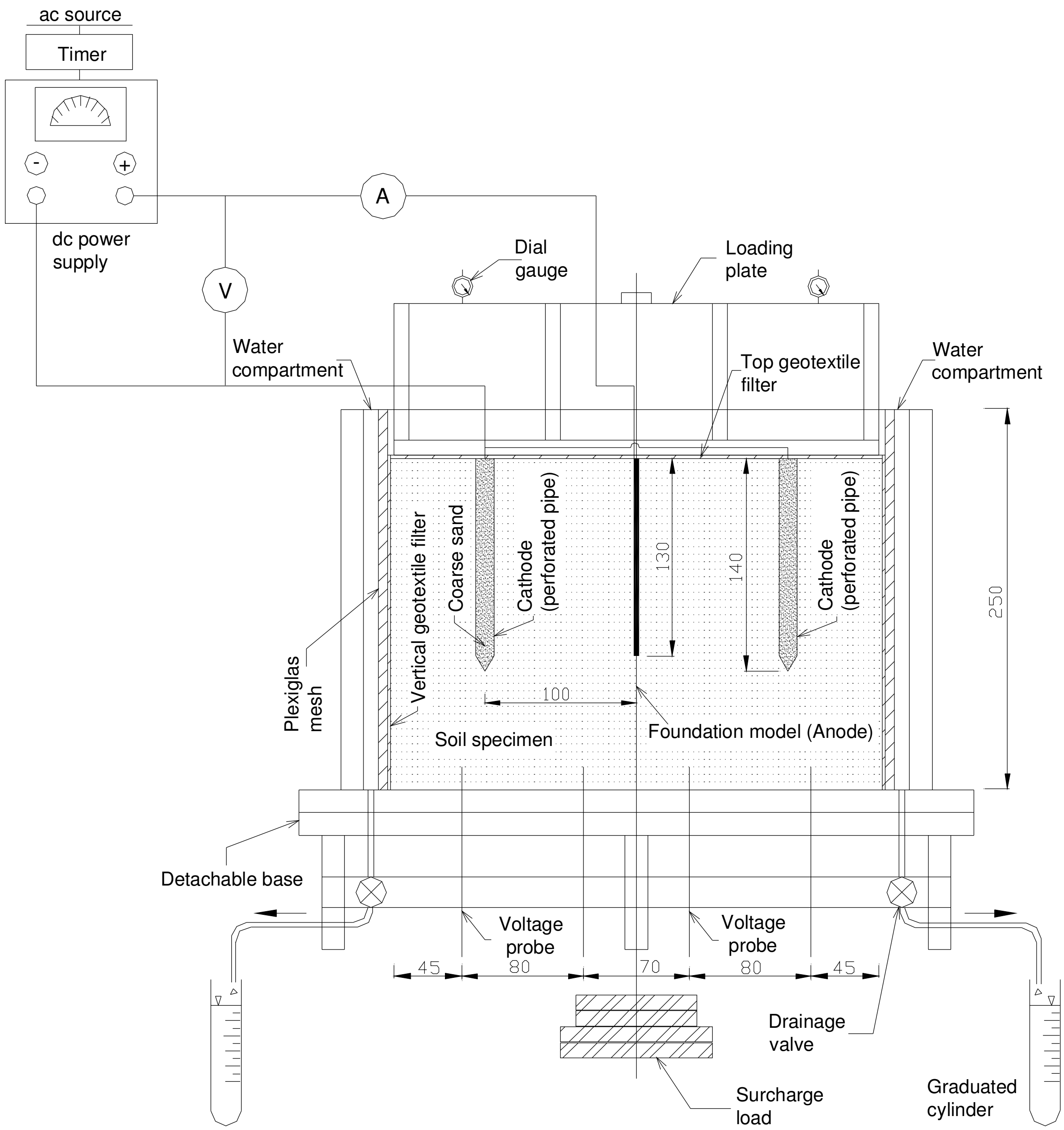

Figure 1. Elevation view of electrokinetic treatment cell

The foundation model served as the anode and two steel pipe electrodes were serving as the cathode. The surcharge load was sustained on the soil specimen during the entire treatment period.

In test series 1, five tests were performed with applied voltages of 0 (control), 5, 10, 15 and 20 V. Current intermittence intervals of 2 min on and 2 min off (β = 0.5) was executed during the tests and each test lasted for 7 days (168 hr). Test series 2 consisted of four tests with applied voltages similar to that of test series 1, continuous dc (β = 1), and energy consumption equivalent to that of the same voltage in series 1. In test series 3 four tests were performed with applied voltages of 5, 10, 15, and 20 V with intermittence interval of 2 min on and 2 min off (β = 0.5) for an energy consumption of 225Whr for each test.

As the electric field was turned-on, part of the water in the soil pores transferred by electro-osmosis toward the two perforated pipe cathodes and via the course sand to the top geotextile filter. The water was then moved by gravity to the two water compartments and then to the graduated cylinders as shown in Figure 1. The volume of water collected during the test, settlement, electric current, and voltage distribution were periodically recorded during the treatment period.

After the completion of the electrokinetic treatment, the electrokinetic cell was placed in a triaxial test machine and the foundation model was loaded to failure in comparison at a rate of 0.3 mm/min. After the triaxial loading, the water content and the undrained shear strength were measured at 12 locations across the cell shown in Figure 2. At each location, two measurements for the undrained shear strength were performed using a Torvane (Soiltest Torvane CL-600A) along with the corresponding water content. Atterberg limits test was performed on the soil from the middle layer adjacent to the foundation model (i.e. B2 and C2).

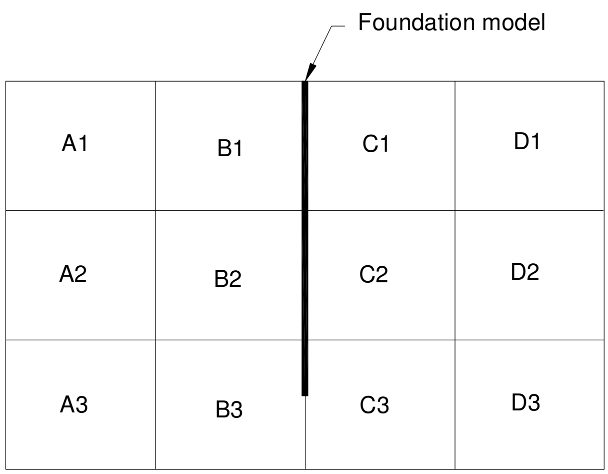

Figure 2. Locations of water content and undrained shear strength, s_u, measurements after the triaxial loading

3 RESULTS AND DISCUSSION

3.1 Electric Current and Energy Consumption

Figure 3 shows the electric current during the 168 hr treatment period for test series1 carried out with current intermittence of 2 min on and 2 min off (β = 0.5). As shown in the figure, the maximum current at the start of the treatment was reported in the test with the highest applied voltage of 20 V followed by that of 15 V, 10 V and 5 V, respectively. The energy consumption was obtained from Equation 5 and summarized in Table 2. As expected, the maximum energy consumption in test series 1 (569 Whr) was obtained in the test with 20 V and the minimum (63 Whr) was obtained in the test with 5 V.

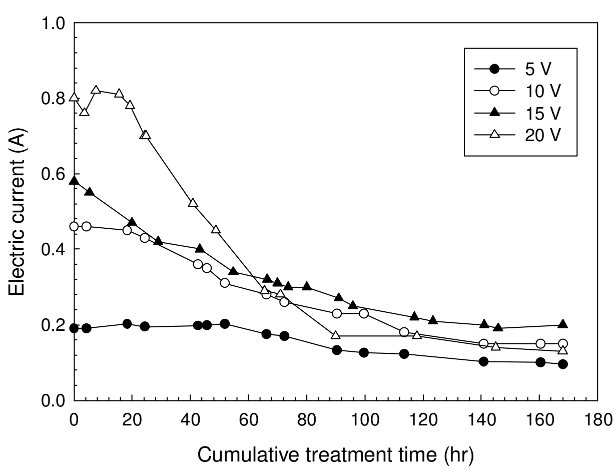

Figure 3. Electric current vs. cumulative treatment time – test series 1 (β = 0.5)

Table 2. Applied voltage and energy consumption

	U_o V	T hr	β	P Whr
Test series 1	0*	168	-	0
	5	168	0.5	63
	10	168	0.5	224
	15	168	0.5	385
	20	168	0.5	569
Test series 2	5	88	1	63
	10	75	1	224
	15	60	1	385
	20	72	1	569
Test series 3	5	741	0.5	224
	10	168	0.5	224
	15	61	0.5	224
	20	25	0.5	224

* The control test

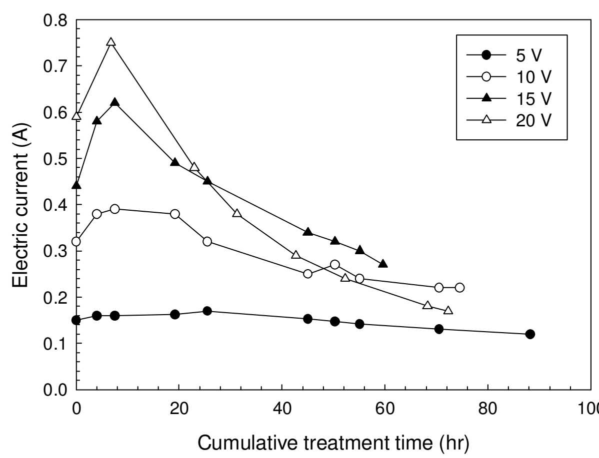

Figure 4. Electric current vs. cumulative treatment time – test series 2 (β = 1)

Figure 4 shows the electric current during treatment for test series 2 carried out with continuous dc (β = 1). As seen in Figure 4, the trends of the electric current are somewhat similar to that of series 1. Energy consumption for each of the four tests in series 2 was kept similar to that of the same voltage in series 1. Since β was 0.5 for series 1 and 1 for series 2, the duration for the tests in series 2 were less than that in series 1 for the same energy consumption. For example, for the test with 5 V, duration of 88 hr was required in series 2 compared to 168 hr in series 1 for the same energy consumption of 63 Whr. As summarized in Table 2, the treatment period in series 2 varied between 60 and 88 hr.

Figure 5 shows the electric current during treatment for test series 3 carried out with current intermittence of 2 min on and 2 min off (β = 0.5). In series 3, the energy consumption was kept constant at 224 Whr for each test. As shown in the figure, a treatment time of 25 hr was required for the test with 20 V compared to 741 hr in the test with 5 V. Treatment times of 168 and 61 hr were needed for the tests with 10 V and 15 V, respectively.

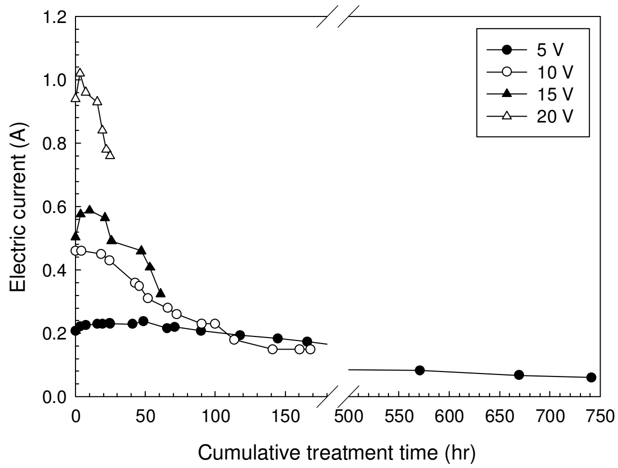

Figure 5. Electric current vs. cumulative treatment time – test series 3 (β = 0.5)

As seen in Figures 3 to 5, the electric current decreased steadily with the treatment time. For example in series 1 (Figure 3) for the test with 20 V, the current decreased from 0.8 A at the start of the treatment to 0.13 A at the end. The decrease in current resulted from the decrease in electrical conductivity of the soil during the treatment. The change in the conductivity of soil during an electrokinetic treatment is a result of two opposing mechanisms. The bulk electrical conductivity of a soil is a product of the electrical conductivity of the two components of the soil, i.e. soil pore fluid (water) and soil solids. In general, the electrical conductivity of the pore fluid is much higher than that of the soil solids and thereby dominates the bulk conductivity of the soil. Therefore, as water is drained out during an electrokinetic treatment process, 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 electrokinetic treatment process (Narasimhan and Ranjan 2000; Mohamedelhassan and Shang 2003). Therefore, as the drainage of water during an electrokinetic treatment process deceases with time, the increase in the electrical conductivity of the pore fluid by the electrolytic reactions may become more dominant than the decrease in soil conductivity resulting from the draining of water. Thus the bulk conductivity of the soil, and thereby the electric current through the soil may increase sometime after the start of an electrokinetic treatment. The increase in current after the start of the treatment was clearly observed in series 2 (Figure 4).

3.2 Axial Load Capacity and Energy Consumption

After the completion of the electrokinetic treatment, the foundation model was axially loaded to failure by a triaxial load frame at a rate of 0.3 mm/min. Figures 6 and 7 show the axial load capacity, Q_c, vs. the vertical displacement of the model for series 1 and series 2, respectively. The axial load capacity at failure, $(Q_c)_f$, is defined as the point of intersection of the axial load capacity-displacement curve and the angle made by the two tangents on the two sides of the sharp bend of the curve (Tani and Craig 1995). The results showed that $(Q_c)_f$ increased in all the tests with electrokinetic treatment as compared with the control test and the increase was proportional to the energy consumption (P). As shown in Figure 6, $(Q_c)_f$ in series 1 (current intermittence of 2 min on and 2 min off, β = 0.5) was 153 N in the test with P of 63 Whr, 172 N with P of 224 Whr, 238 N with P of 385 Whr and 334 N with P of 569 Whr compared to $(Q_c)_f$ of 19 N in the control (P = 0). This represents a net increase between 7 to 16.6 times $(Q_c)_f$ of the control test. In series 2 (continuous current, β = 1), Figure 7 shows that $(Q_c)_f$ was 54 N in the test with

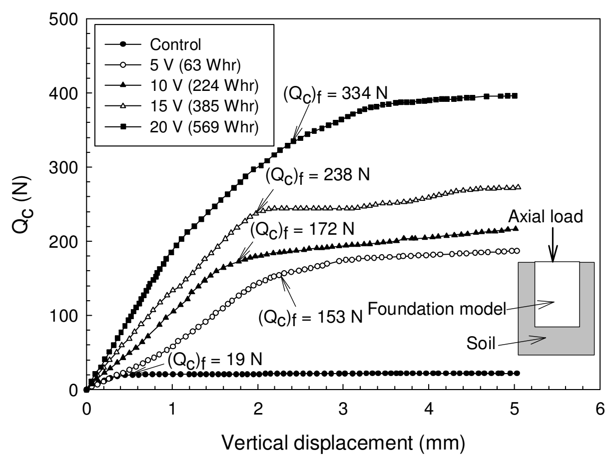

Figure 6. Axial load capacity, Q_c, vs. vertical displacement of the foundation model – test series 1 (β = 0.5)

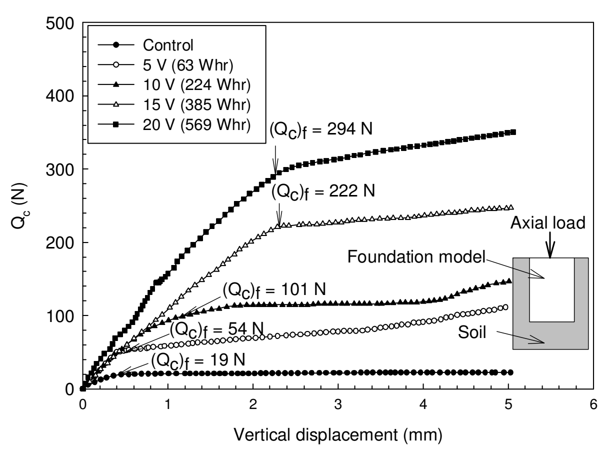

Figure 7. Axial load capacity, Q_c, vs. vertical displacement of the foundation model – test series 2 (β = 1)

P of 63 Whr, 101 N with P of 224 Whr, 222 N with P of 385 Whr and 294 N with P of 569 Whr. This represents a net increase of 1.8 to 14.5 times $(Q_c)_f$ of the control test. It must be noted that the duration of the treatments in series 2 varied between 60 and 88 hr compared to 168 hr in series 1.

Figure 8 shows $(Q_c)_f$ vs. the energy consumption, P, for series 1 and series 2. As shown in the figure, $(Q_c)_f$ in series 1 (β = 0.5) was higher than $(Q_c)_f$ in series 2 (β =1) at the same energy consumption. The superior results obtained in series 1 with current intermittence are in agreement with the results from previous studies (e.g. Sprute and Kelsh 1975; Micic et al. 2001; Mohamedelhassan and Shang 2001). The enhanced improvement by current intermittence may be attributed to the charge depolarization associated with current interruption. A clay-water-electrolyte system consists of negatively charged clay particles surrounded by electrical diffuse double layer (Mitchell and Soga 2005). Under a dc electric field, the clay particles and the double layer will polarize (i.e. the charges redistribute) with the polarization of the double layer being predominant. The charge orientation that resulted from polarization is against the applied electric field, which reduces the efficiency of electrokinetics by decreasing the efficiency of electric field to move water out of the soil pores. This was confirmed during this study as the water contents of soil specimens across the cell in series 1 were found to be less than the water contents in series 2. Accordingly, the shear strength values in series 1 were found to be higher than their counterparts in series 2 as will be discussed in the following sections.

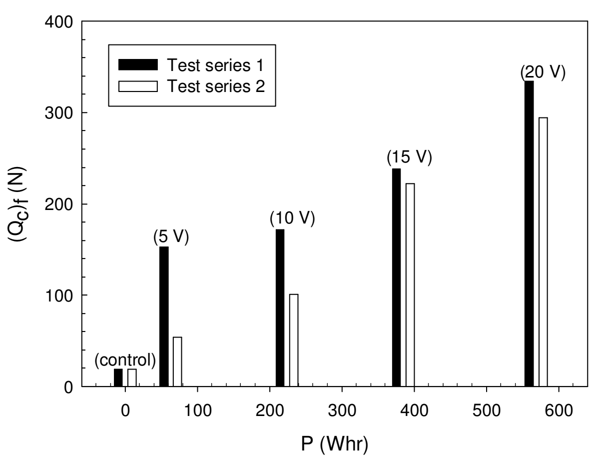

Figure 8. Axial load capacity at failure, $(Q_c)_f$, vs. energy consumption, P for test series 1 and test series 2

Figure 9 shows Q_c vs. the vertical displacement in test series 3 carried out with current intermittence intervals of 2 min on and 2 min off (β = 0.5) to an energy consumption of 224 Whr for each test. As shown in the figure, $(Q_c)_f$ varied slightly between 172 N to 185 N. This indicates that for the range of voltages tested, the axial load capacity of the model is generally independent of the magnitude of the applied voltage and the treatment time and primarily dependent on the energy consumption. $(Q_c)_f$ was 181 N for the test with 20 V and completed in only 25 hr (approximately 1 day) compared to $(Q_c)_f$ of 185 N in the test with 5 V and completed in 741 hr (approximately 1 month). Shortening the duration of the treatment to one day rather than one month and almost achieving the same improvement in $(Q_c)_f$ can provide significant savings and make the technique more appealing.

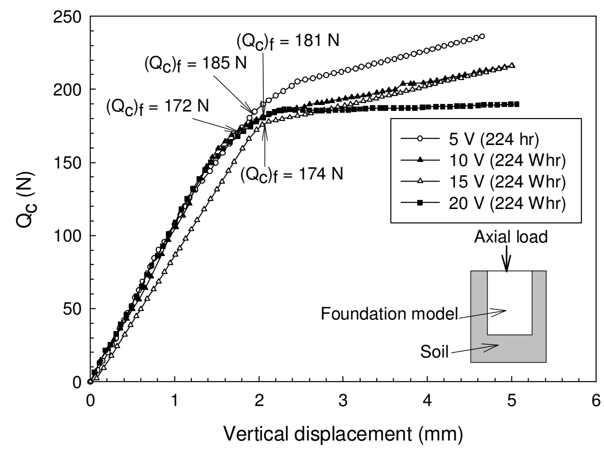

Figure 9. Axial load capacity, Q_c, vs. vertical displacement of the foundation model – test series 3

3.3 Undrained Shear Strength and Atterberg Limits

As the foundation model represents a section of a deep foundation element, in clayey soils the axial capacity of a deep foundation is function of the undrained shear strength at the soil-foundation interface. Figures 10 and 11 show the undrained shear strength, s_u, across the cell measured after the completion of the triaxial loading. The shown value of shear strength at each location was averaged from six measurements (e.g. at 40 mm from the vertical geotextile filter, two measurements for each of samples A1, A2 and A3). Figures 10 and 11 show that electrokinetic was effective in drastically increasing the undrained shear in the vicinity of the foundation model (B_j and C_j) as compared with the control and thereby significantly increased the axial load capacity of the model as discussed in the previous sections. As seen in the figures, away from the model (A_j and D_j) the increase in shear strength was less drastic. Focusing the treatment and the shear strength improvement in the vicinity of a foundation element is very important in reducing the energy consumption of an electrokinetic treatment process for full scale applications, and yet can lead to a significant increase in the axial load capacity of the element as evidence by the results.

The Atterberg limits for soil in middle layer adjacent to the foundation model (i.e. B2 and C2) are summarized in Table 3. As seen from the table, in all tests the liquid limit, LL, and the plastic limit, PL, increased after the electrokinetic treatment. At the liquid limit, a clayey soil has virtually no shear strength when remolded. A higher liquid limit means that the soil will lose its shear strength at higher water content when remolded. Accordingly, the increase in the liquid limit after the electrokinetic treatment is arguably an improvement to the strength properties of the soil as the treated soil will retain some of its shear strength when remolded at water content equivalent to its original liquid limit.

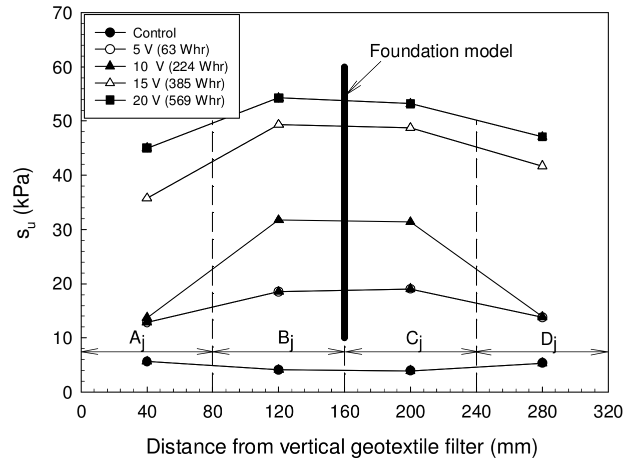

Figure 10. Undrained shear strength, s_u, across the cell - test series 1 (β = 0.5)

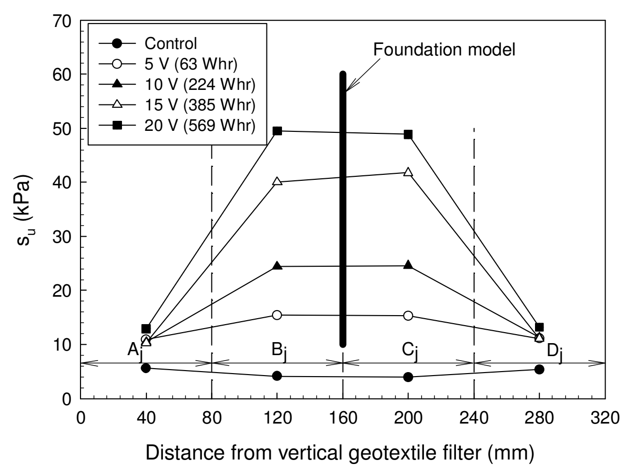

Figure 11. Undrained shear strength, s_u, across the cell - test series 2 (β = 1)

3.4 Energy Consumption and Corrosion of the Foundation Model

The mass of the foundation model prior to- and after electrokinetic treatment are summarized in Table 3. In test series 1 and 2, the loss in mass was found to be proportional to the energy consumption. This is while the loss in the mass was negligible in the control test (0.4%), a substantial loss of 11.4% was reported in the test with 569 Whr in series 2. Table 3 shows the loss in the mass of the model in series 1 (current intermittence, β = 0.5) to be less than the loss in series 2 (continuous dc, β = 1). The reduction in corrosion by intermittence current was also report by Micic et al. (2001). For the same energy consumption, series 3 showed that the loss decreased with the increase in the applied voltage and the decrease in the treatment time.

Table 3. Loss corrosion of the foundation model and Atterberg limits after the electrokinetic treatment

	U_o V	P Whr	Mass prior to treat. g	Mass after treat. g	Mass loss %	LL	PL
Test series 1	0	0*	255.5	254.4	0.4	39	18
	5	63	251.8	238.9	5.1	47	21
	10	224	253.5	232.2	8.4	43	20
	15	385	253.4	230.3	9.1	42	20
	20	569	254.8	227.8	10.6	41	19
Test series 2	5	63	256.0	235.0	8.2	38	21
	10	224	256.9	233.3	9.2	50	21
	15	385	254.3	228.0	10.3	48	21
	20	569	254.6	225.6	11.4	44	19
Test series 3	5	224	269.7	236.9	12.2	45	19
	10	224	253.5	232.2	8.4	43	20
	15	224	253.5	240.8	5.0	42	20
	20	224	252.9	245.1	3.1	40	19

* The control test

4 CONCLUSIONS

Three test series were carried out to investigate the effect of energy consumption on Q_c of a foundation model embedded in soft clay soil. In series 1, voltages of 0 (control), 5, 10, 15, and 20 V with current intermittence of 2 min on and 2 min off (β = 0.5) were applied during a 7 day treatment period. Series 2 was performed with duplicates voltages to series 1 and continuous current (β = 1) for energy consumptions similar to series 1. In test series 3, voltages of 5, 10, 15, and 20 V with current intermittence of 2 min on and 2 min off (β = 0.5) were applied for an energy consumption of 224Whr for each test. After the electrokinetic treatment, the foundation model was axially loaded to failure by a triaxial load frame. The results of the study showed that:

- In test series 1 and 2, electrokinetics had significantly increased Q_c of the foundation model and that the increases were proportional to energy consumption. The maximum increases were obtained in the tests with current intermittence (series 1). The maximum axial load capacity after the treatment was 334 N compared to 19 N in the control test.
- In test series 3, comparable axial load capacity values were obtained the tests. This indicates that similar increases in the axial load capacity are to be expected for the same energy consumptions in spite of the differences in the applied voltage and duration of the treatment.
- The results showed that electrokinetic treatment had significantly increased the undrained shear strength in the vicinity of the foundation model and increases both the liquid and the plastic limits.
- The loss in the mass of the foundation model by corrosion was proportional to the energy consumption

and the current intermittence had reduced the corrosion of the model.

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