Axial response of piles in electrically treated clay

M. Abdel-Meguid, M.H. El Naggar, and J.Q. Shang

Abstract: Improvement of the shear strength of soft clayey soils around steel pipe piles using high-voltage electrokinetics is investigated in the present study. The experimental setup of a large-scale testing facility is described. Four model piles were installed in two identical cylinders filled with simulated marine sediment. Five electrically insulated electrodes were installed close to the piles to apply a high-voltage electric field in the test cylinder. Negative direct current voltages of –20, –30, and –10 kV were applied in three phases, respectively, for 33 days in the treatment cylinder. Axial compression and pullout pile load tests were performed and the results were compared for both cylinders after each phase of treatment. The pile response is presented in terms of the experimental load deflection curves. It is observed that the axial capacity was increased 30, 29, and 8% after the first, second, and third treatment phases, respectively. The pullout capacity was increased due to the treatment by 11, 23, and 12% after the first, second, and third treatment phases, respectively. Further development of this technique may provide potential solutions for the improvement of soft marine clays, and ultimately it could be applied in the field to rehabilitate existing offshore foundations.

Key words: electrokinetics, piles, marine clays, soil improvement, bearing capacity, axial loading.

Résumé : On étudie ici le gain de résistance au cisaillement de sols argileux mous autour de pieux en acier, gain obtenu par un traitement électrocinétique à haut voltage. On décrit le montage expérimental dans installation d'essai à grande échelle. Quatre pieux modèles ont été placés dans deux cylindres identiques remplis d'un sédiment marin artificiel. Cinq électrodes isolées électriquement ont été installées à proximité des pieux pour appliquer un champ électrique de haut voltage dans le cylindre d'essai. Des différences de potentiel négatives en courant continu de –20, –30, et –10 kV ont été appliquées successivement et pendant 33 jours dans le cylindre de traitement. Des essais de compression axiale et d'arrachement des pieux ont été effectués et les résultats ont été comparés pour les deux cylindres après chaque phase de traitement. La réponse du pieu est présentée sous la forme de courbes expérimentales chargement/déplacement. On a pu observer que la capacité axiale augmente de 30%, 29% et 8% après les phases un, deux et trois du traitement. De même la résistance à l'arrachement a été améliorée de 11%, 23% et 12% respectivement. Un développement futur de cette technique pourrait offrir des solutions pour améliorer les argiles marines molles, ce qui permettrait de réhabiliter sur place des fondations en mer existantes.

Mots clés : électrocinétique, pieu, argiles marines, amélioration du sol, capacité portante, chargement axial.

[Traduit par la Rédaction]

Introduction

Traditional methods of soil improvement are not cost efficient for pile foundations, and in some cases are impossible to execute. New soil improvement techniques are therefore needed, especially in the offshore environment. As a result of the advancing technology in electrostatics, two approaches of electrical strengthening of soft clay have been studied over the years. Electroosmosis, the first approach, involves the transport of pore water under the influence of a direct current (dc) electric field. Soderman and Milligan (1961) used electroosmosis to increase the bearing capacity of steel H-piles in the Big Pic River Bridge project. It was reported that the pile capacity was increased 2.5–3 times.

The second approach, namely, high-voltage electrokinetics, involves the application of a high-voltage electric field through electrically insulated electrodes. The improvement of the clay properties in this technique is primarily attributed to two mechanisms, namely, electrophoresis and dielectrophoresis (Shang and Dunlap 1996). The former is generated by a dc electric field, whereas the latter is attributed to the action of a nonuniform electric field, i.e., the electric field varies as a spatial function.

The application of a high-voltage dc to clayey soils via insulated electrodes was first attempted by Shang and Dunlap (1996, 1998). They reported that the dc voltage application resulted in considerable strengthening effects (up to 267%) of soft marine sediments. Further, the pullout resistance of anchor models (steel plates and aluminum cylinders) was significantly increased (up to 80%).

To date, the mechanism of the application of a high dc voltage is still under investigation. In the present study, an attempt has been made to further explore the effects of high-

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voltage electrokinetics towards the improvement of the pile capacity and enhancement of pile performance under axial loading conditions. Laboratory tests were conducted to investigate the effect of applying a high voltage to improve the engineering properties of the local soil around the piles and its impact on the pile response to different types of loading. High dc voltages with different intensities were applied through insulated electrodes for a certain time period. Soil shear strength and pile loading capacity were tested after each application and compared with the initial soil and pile conditions.

The experiments were conducted in the Structural Laboratory at the University of Western Ontario. The testing facility was designed to allow both soil treatment and model piles testing. Three series of tests were carried out on model piles installed in simulated marine clay to investigate the effects of the high-voltage electrokinetic treatment on soil and pile behaviour.

Program of laboratory study

To study the effects of high-voltage electrokinetics on the soil properties in the vicinity of the piles and the pile response to static and cyclic loading, the testing program in this study consisted of three phases. Previous studies (Lo et al. 1994; Shang and Dunlap 1996, 1998) have shown that the strengthening effect of high-voltage electrokinetics takes place after a longer period of application than electro-osmosis, typically in the range of 20–30 days. Therefore, in this test series a high voltage was applied for 33 days in each phase in the treatment cylinder with the same electrode configuration and the same piles and electrode arrangement. A series of soil and pile testing was carried out and the results were compared for both cylinders after each phase. The initial soil properties and pile capacity were measured prior to the treatment.

Testing environment and equipment

Two cylinders were used to conduct the test, one to implement the high-voltage treatment (test cylinder), and the other as a control cylinder to compensate for the effect of natural drying and aging of the soil. The body of each cylinder was made of a steel tube with an internal diameter of 1.37 m, wall thickness of 13 mm, and depth of 1.52 m. In each cylinder, four piles were installed at a spacing of about 9*B*, where *B* is the diameter of the piles. A drainage outlet was made at the bottom of each cylinder and covered with a geotextile filter at the inner perimeter of the cylinder. The outlet was controlled with a valve to permit drainage of water from the clay. Air bladders were lined on the internal perimeters and connected to an air line controlled by a pressure regulator to apply a confining pressure to the soil in both cylinders simultaneously to accelerate the consolidation process during the preparation of the test soil. A sand layer 100 mm thick was laid underneath the geotextile filter at the bottom of each cylinder. The testing area was fenced, and the cylinders and the surrounding fence were connected to the ground return for safety reasons. The vessels in which the clay was consolidated and the tests carried out are shown schematically in Fig. 1.

Model piles

The model piles were made of hollow standard steel pipes with an outside diameter of 60 mm and inside diameter of 57 mm. Total pile length was 1.42 m, with an average embedment length of approximately 1.12 m. These dimensions corresponded to a length (L) to diameter (B) ratio of 19 and a moment of inertia of 1.18×10^{-7} m^4. The Young's modulus of the steel was 210 GPa, and its unit weight was 53.945 N/m. The chosen L/B ratio represented a typical value for short rigid piles (Poulos and Davis 1980). The piles were fitted with standard flanges with four holes to facilitate both static axial compression and pullout loading. The model piles and their locations are shown schematically in Fig. 2.

After the clay bed had been prepared, the pile locations were determined using four wires extended over the cylinders such that minimum spacing between the piles was 0.55 m (9*B*). The piles were manually pushed into the clay until a certain depth was reached, then a concrete block was used to drive the piles to the required embedment depth of 1.12 m. A level was used to check the pile verticality during the installation process.

Static axial loading setup

A simple mechanism was used for the static axial loading tests to apply the vertical loads and to measure the displacement of the pile. Standard cast-iron weights were used to apply the load incrementally to the flange of the tested pile. To monitor the vertical displacement of the pile during the axial loading test, a fixed reference beam holding displacement gauges was used. The reference beam was composed of a steel channel rigidly connected at both sides to the cylinder with steel clamps. Two dial gauges with an accuracy of 0.01 mm mounted at the pile head were used to measure the average pile displacement corresponding to each load increment during both static and cyclic loading tests.

Pullout loading setup

The pullout pile resistance measurement was achieved using a loading system comprised of two 40 mm i.d. steel pulleys with a knife-edged inner perimeter. The first pulley was fixed to the top beam of a rigid steel frame and mounted vertically with the pile and the second was fixed to the rim of the cylinder through a steel bracket. The pulleys were adjusted so that a steel wire connected at one end to the pile flange passed over the two pulleys and held a hanger at the other end. The pullout load was achieved by adding standard weights incrementally to the load hanger. The steel frame was rigidly fixed to the cylinder using four bolts.

The vertical displacement of the pile head was measured using two dial gauges mounted at the top of the pile flange and attached to the frame using a magnetic base holder. The pullout test setup is shown schematically in Fig. 3.

Electrode

The high voltage must be applied through electrically insulated electrodes due to the clay's electrically conductive nature. Five electrodes made of solid copper rods 9 mm in diameter and 1.22 m in length and electrically insulated with shrinkable Teflon tubing were used in the experiments. Threaded holes 3 mm in diameter were drilled through the

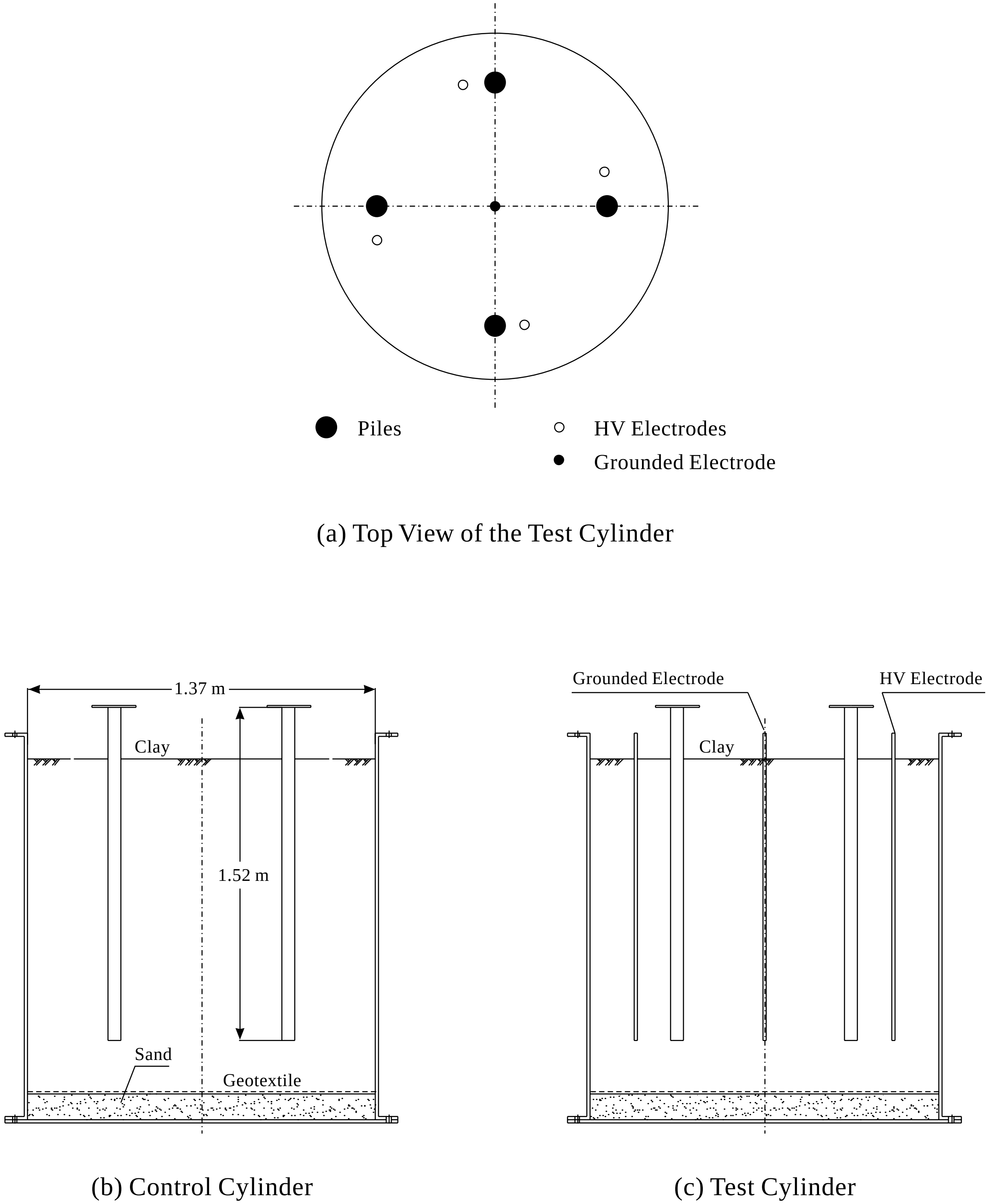


Fig. 1. Schematic of the testing facility: (*a*) top view of the test cylinder; (*b*) control cylinder; (*c*) test cylinder. HV, high voltage.

top of the electrodes to fit brass bolts to facilitate the wiring connection between the electrodes. A dc voltage can cause charge concentration around the electrodes. This effect caused by the sharp edges at the interface between the electrode and the insulation material was minimized by smoothing the bottom of the electrode to a semispherical shape.

An important criterion in the design of the electrodes was that the maximum field intensity must not exceed the dielectric strength of the insulation material. TFM Inner Melt Heat shrinkable Teflon tubing with 1.397 mm thickness and a dielectric constant of 2.2 was used to satisfy this criterion. Since the specified Teflon tubing comes in lengths of 609.6 mm (2 ft), it was necessary to connect two tubes to insulate one electrode. A heat gun was used to shrink the tubes so that each two tubes overlapped about 30 mm and allowed about 20 mm for the tip insulation as shown in Fig. 4. An-

Fig. 2. Geometry and location of the model pile: (*a*) elevation; (*b*) pile cross section; (*c*) locations.

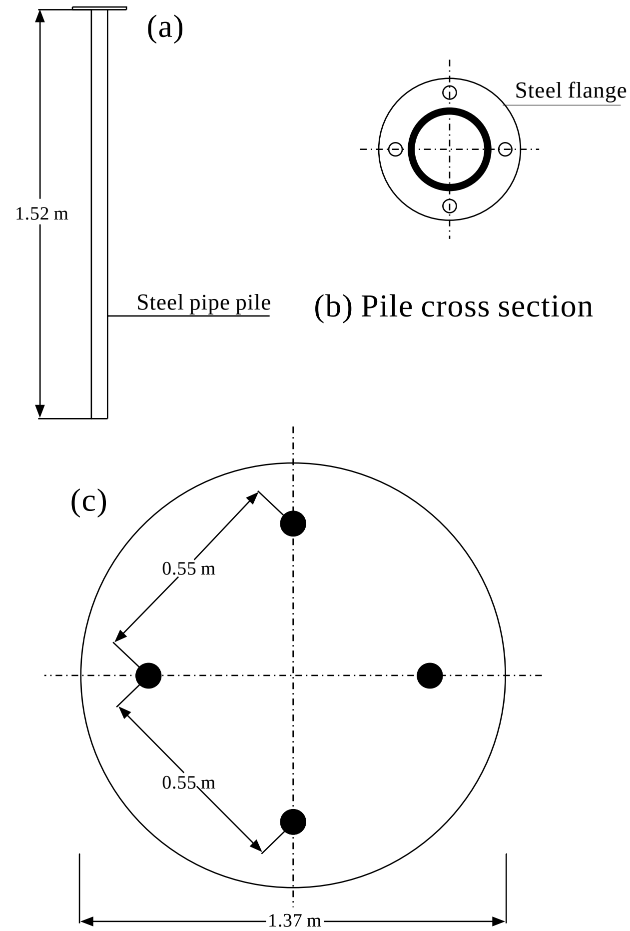
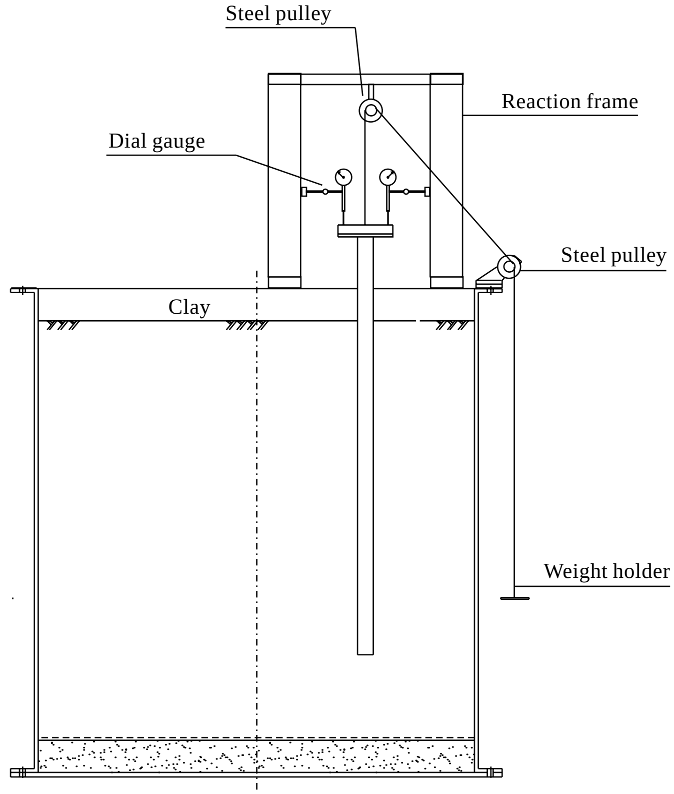


Fig. 3. Pullout test setup.



other piece of polyolefin flexible adhesive lined shrinkable tubing was used to cover the splice area to strengthen the connection between the two tubes. The electrode tip was insulated by filling the end of the tube with transparent silicon gel and allowing it to dry.

The embedded length of the electrode into the soil was 0.90 m. Five electrodes were installed into the treated cylinder so that a central grounded electrode was located coaxially within four outer high-voltage electrodes. The high-voltage electrodes were installed close to the piles to maximize the concentration of the electric field around the piles. The distance between the electrode and the pile was designed to be 150 mm based on the consideration that the electrodes should be close to the piles and at the same time a voltage discharge through the air between the electrodes and the piles should be avoided.

The high-voltage electrodes were connected using high-voltage cables attached to each electrode with a brass bolt. Then one of the four high-voltage electrodes was connected to the high-voltage power supply. The high-voltage electrodes were installed in the vicinity of the piles to achieve high electric field intensity in this region.

High-voltage power supply

Two different dc power supplies with different capacities were used in the present study to investigate the effect of applying different high-voltage intensities on the soil behaviour and pile response to different loads. A negative polarity was used for both power supplies. A power supply with an output voltage of 0–22 kV and output current of 0–35 mA was used to apply –20 kV in the first phase of testing. Later, another power supply with an output voltage of 0–36 kV and output current of 0–30 mA was used to apply –30 kV in the second testing phase and –10 kV in the third testing phase. Both power supplies had a self-shutdown feature when the current between the high-voltage electrode and the grounded electrode exceeded 2 mA, and the current was monitored by the meter (in mA) on the power supply. There was no measurable conducting current registered during the entire testing period.

Settlement pins

The settlement of the clay surface was monitored during the treatment process. Four settlement pins were distributed at the clay surface in each cylinder; the pin locations are shown in Fig. 5. A telescope with an accuracy of 0.10 mm was fixed between the two cylinders to measure the settlement of each pin, and the readings were recorded at different time intervals during the high-voltage application.

Soil properties

The soil used was dark brown clay from a natural deposit recovered from London, Ontario. The soil properties are summarized in Table 1. The clay mineralogy was analyzed using X-ray and chemical methods. The dominant clay minerals were illite and chlorite, while quartz and carbonate were the major nonclay minerals. The grain-size distribution curve shown in Fig. 6 indicated that the soil consisted of

Fig. 4. Electrode and insulation details.

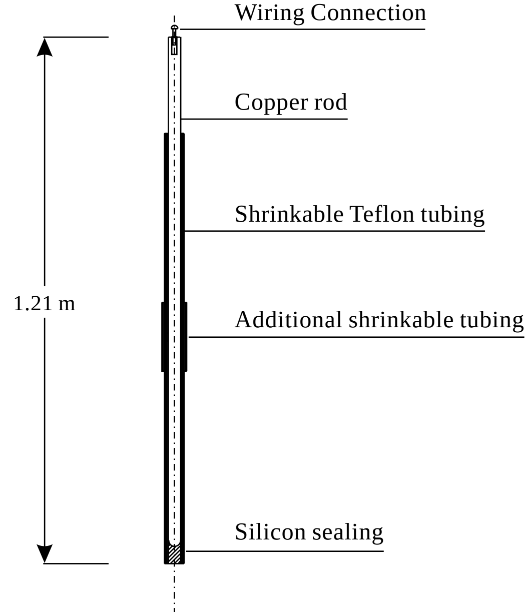
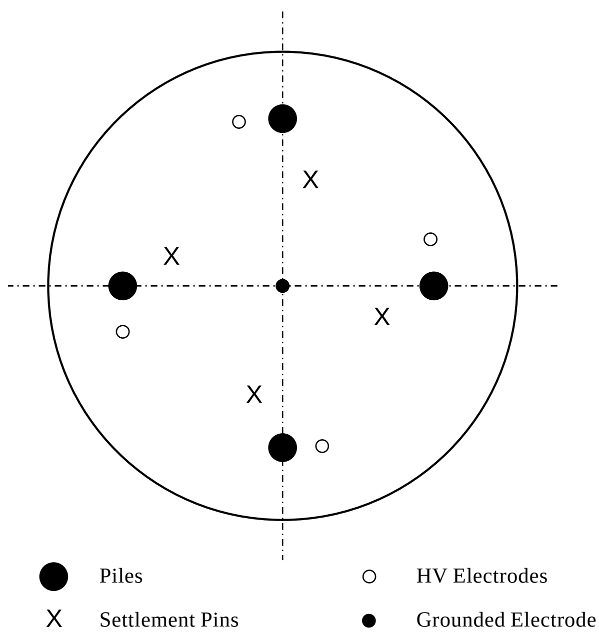


Fig. 5. Location of settlement pins.



about 42% clay and 24% silt according to the MIT classification system. The organic content of the soil was 1.84%. The conductivity of the prepared clay slurry was determined from laboratory measurements as 0.65 S/m.

Soil preparation and initial conditions

The soil was first placed in an open area to air dry. The soil was crushed in two stages into small particles using a Bannerman Top Dresser. The clay chunks were crushed into smaller pieces, and then the small pieces were crushed into fine particles and passed through a sieve with 1 in. (25.4 mm) openings to separate any gravel or uncrushed clay pieces.

Table 1. Summary of the properties of the natural soil used in the study.

Water content (%)	41
Liquid limit (%)	43.3
Plastic limit (%)	32.6
Specific gravity	2.65
Carbonate content (%)	11.2
Quartz (%)	34
Specific surface (m^2/g)	10.6
Cation exchange capacity (mequiv./100 g of clay)	34.7
Salinity (g/L)	6
pH	7.06

The prepared dried soil was blended with a sodium chloride solution at a concentration of 10 g/L to obtain a soil composition closer to that of the offshore environment and poured into cylinders in 10 layers to saturate the soil and allow for self-weight consolidation. A steel rod was pushed several times in each layer to remove any entrapped air from the soil. The drainage valves were kept closed during the process. After all the soil had been poured, an air pressure of 30 kPa was applied to both cylinders through the air bladders. The bottom drainage valves were opened to allow drainage. During the application of the air pressure the soil surface moved upward, so the soil surface was covered with steel plates to prevent the soil movement.

After 1 week, the clay surface had settled about 100 mm. The cylinders were then topped up with soil that had been thoroughly mixed with sodium chloride solution at the same concentration. The drainage valves were closed after 40 days of consolidation and salty water was added to keep the clay surface submerged during the treatment and testing processes. Soil samples were recovered from the cylinders to determine the liquid limit and plastic limit of the clay. Furthermore, the water content and shear strength were measured at different locations in three layers. The locations of the testing points are shown in Fig. 7.

After all the piles and electrodes had been installed, the soil surface was leveled and marked at three identical locations in both cylinders for the purpose of soil sampling and shear strength measuring. The undrained shear strength of the soil was measured by a laboratory vane tester during all phases of the experimental study. An extension rod 0.75 m in length was designed and marked at 0.30 m intervals to enable the vane tester to reach different depths in the cylinder. The undrained shear strength was measured at three depths 0.30 m apart starting from the soil level.

The water-content samples were recovered at each depth from the sustained soil between the vane blades. One sample was used to determine the Atterberg limits of the soil. Shear strength and water content of the soil at each depth are summarized in Table 2. The undrained shear strength at each depth is shown in Fig. 8. The water content across the cylinders ranged between 36.39 and 45.3%, and the shear strength ranged between 4.5 and 14.5 kPa. The water content and shear strength of the soil in both cylinders (at the locations of measurement) were consistent and therefore the criterion of the control cylinder at this stage of the experimental work was satisfied.

Test results

High-voltage application (phase 1)

A –20 kV dc voltage of negative polarity was applied to the treatment cylinder for a period of 33 days in the first phase of this study. The settlement of the clay surface at both cylinders was monitored during the treatment process by measuring the relative displacement between the settlement pins and a fixed object. The negative high voltage was applied to the outer electrodes continuously during the test period without interruption. The critical factor during the high-voltage process was the electrode insulation. The connection between the two Teflon tubes over the electrode and the tip insulation was not strong enough to resist the applied voltage at the initial stage of the high-voltage application. Therefore, a short circuit between the high-voltage electrode and the grounded electrode caused overload and shut off the power supply. It should be noted that the power supply was automatically shut down immediately after (almost simultaneously) the short circuit occurred. Therefore, it would not generate any excessive heating effect. The connection was then strengthened by adding another insulation layer at the overlapping area. Furthermore, the seal at the end of the electrodes was replaced and a piece of adhesive shrinkable tubing melted and closed at one end was used to protect the Silicon insulation during the electrode installation. The high voltage was turned off and a series of soil and pile tests were carried out in both cylinders after 33 days of treatment.

Fig. 6. Grain-size distribution of the soil.

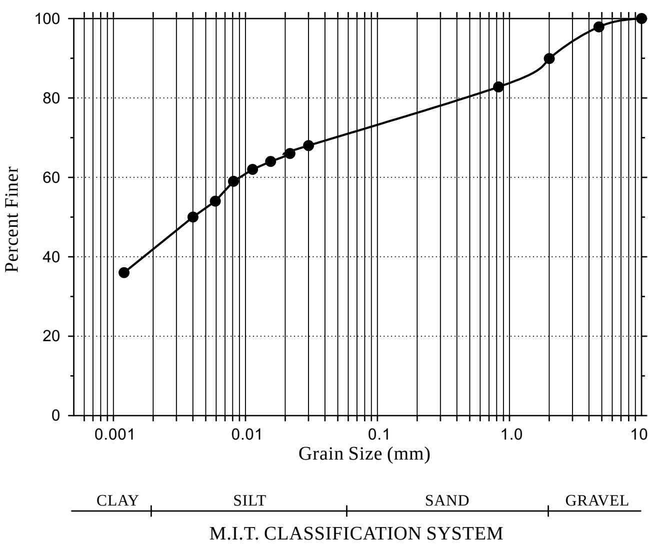


Fig. 7. Location of soil testing points.

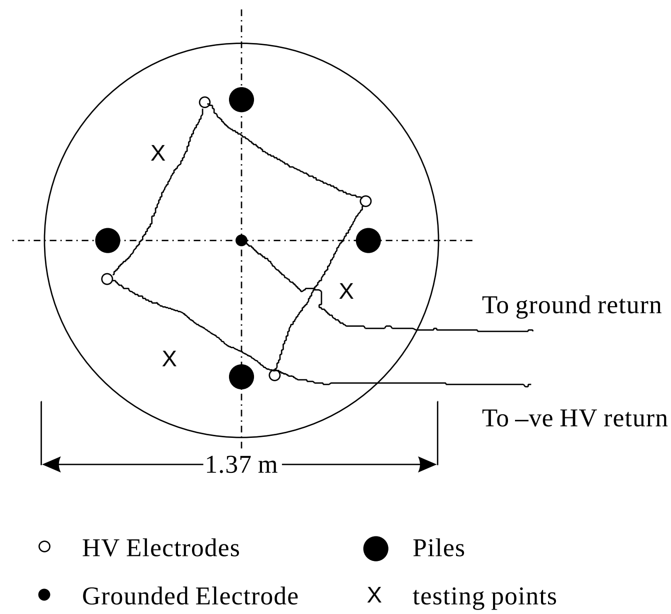


Table 2. Shear strength and water content of the soil before treatment.

Depth (m)	Control cylinder: Shear strength c_u (kPa)	Control cylinder: Water content w (%)	Treated cylinder: Shear strength c_u (kPa)	Treated cylinder: Water content w (%)	Difference[a]: Δc_u (kPa)	Difference[a]: Δw (%)
Location 1						
0.3	5.0	36.39	4.5	43.4	–0.50	7.01
0.6	6.2	37.89	8.0	39.18	1.80	1.29
0.9	10.2	41.21	9.5	42.50	–0.70	1.29
Average	7.13	38.49	7.33	41.69	0.2	3.2
Location 2						
0.3	5.2	42.7	5.5	42.7	0.30	0.00
0.6	7.0	42.14	7.0	41.3	0.00	–0.84
0.9	11.2	40.78	11.5	42.0	0.30	0.30
Average	7.8	41.87	8.00	42.00	0.2	0.13
Location 3						
0.3	4.9	41.70	5.2	44.39	0.3	2.69
0.6	14.5	39.04	13.2	40.25	–1.30	1.21
0.9	9.0	41.30	9.5	45.29	0.50	3.99
Average	9.46	40.68	9.30	43.31	–0.16	2.63

[a] $\Delta c_u = c_u$(treated) – c_u(control); $\Delta w = w$(treated) – w(control).

Fig. 8. Shear strength before treatment.

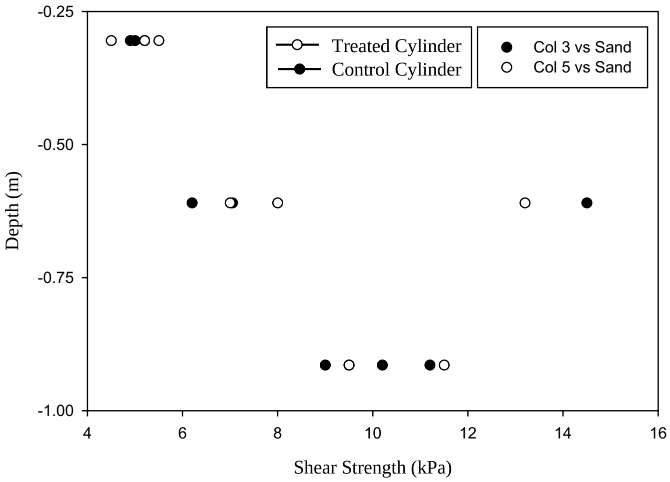


Fig. 9. Shear strength after the first treatment phase.

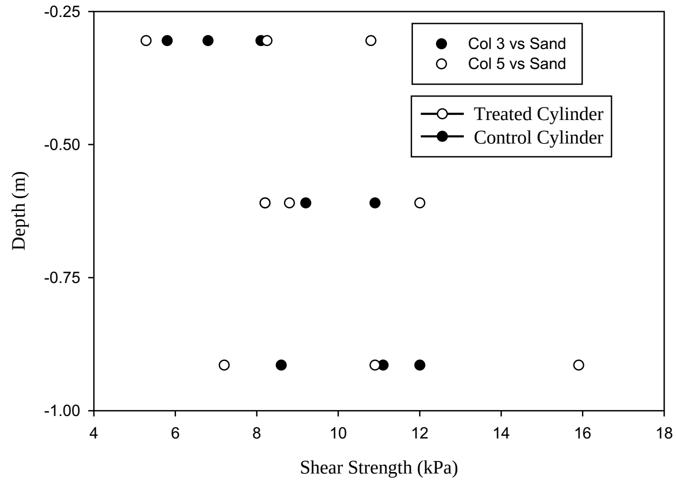


Table 3. Shear strength and water content of the soil after the first phase of treatment.

	Control cylinder		Treated cylinder		Difference	
Depth (m)	Shear strength c_u (kPa)	Water content w (%)	Shear strength c_u (kPa)	Water content w (%)	Δc_u (kPa)	Δw (%)
Location 1						
0.3	5.80	40.90	5.28	39.17	–0.52	–1.73
0.6	8.20	41.66	8.25	41.18	–0.48	–0.48
0.9	11.1	39.13	10.80	40.94	–0.30	1.81
Average	8.36	40.49	7.33	41.69	–0.43	–0.13
Location 2						
0.3	8.10	41.37	8.20	41.14	0.10	–0.23
0.6	9.20	40.48	8.80	41.95	–0.40	1.47
0.9	12.0	40.98	12.0	37.40	0.00	–3.58
Average	9.76	40.94	9.66	40.16	–0.10	–0.78
Location 3						
0.3	6.80	41.18	7.2	40.35	0.4	–0.65
0.6	10.9	40.06	10.9	41.73	0.0	1.67
0.9	8.60	42.29	15.9	38.66	7.30	–3.63
Average	8.76	41.17	11.33	40.24	2.57	–0.93

Treatment effect on soil properties

To investigate the effect of the high-voltage application on soil properties, the water content and shear strength were measured at different points in three layers in the cylinders. The undrained shear strength and water content of the soil (at the locations of measurement) in the treated and control cylinders are summarized in Table 3. It was observed that the overall water content (at the locations of measurement) decreased 4.2% in the treated cylinder and 0.65% in the control cylinder. The average undrained shear strength at both cylinders indicated that the shear strength (at the locations of measurement) increased 13% in the test cylinder and 6% in the control cylinder. The results of the shear strength at each depth are shown in Fig. 9. The shear strength increased with depth and the maximum difference was observed at a depth of 0.90 m from the soil surface. The observed soil settlement after treatment was fairly small, which is consistent with the decrease in soil water content.

Treatment effect on axial pile capacity

The load was applied with a constant time interval between increments of 2.5 min until the pile failed. A load increment of 19.6 N (2.0 kg) was adopted throughout the tests. The Davisson's failure criterion (Davisson 1970) is used throughout this study to determine pile capacity.

The load–displacement relationship obtained is shown in Fig. 10. Both piles exhibited the same behaviour, i.e., the displacement increased as the load increased in an almost linear relationship until a load of 0.28 kN was reached. Afterwards, the pile in the control cylinder started to resist no load and failed suddenly. However, the pile in the treated cylinder resisted a load up to 0.36 kN and then started gradually to present excessive settlement. The capacity of the pile in the treated and control cylinders, according to Davisson's failure criterion, was 0.362 and 0.277 kN, respectively, with an increase of about 30% after treatment. This behaviour indicates that the adhesion between the clay

Fig. 10. Axial load – displacement curve after the first treatment phase.

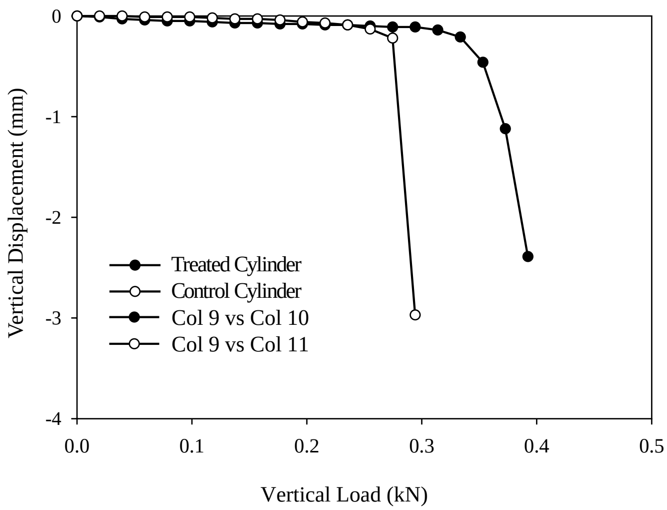


Fig. 11. Pullout resistance of piles after the first treatment phase.

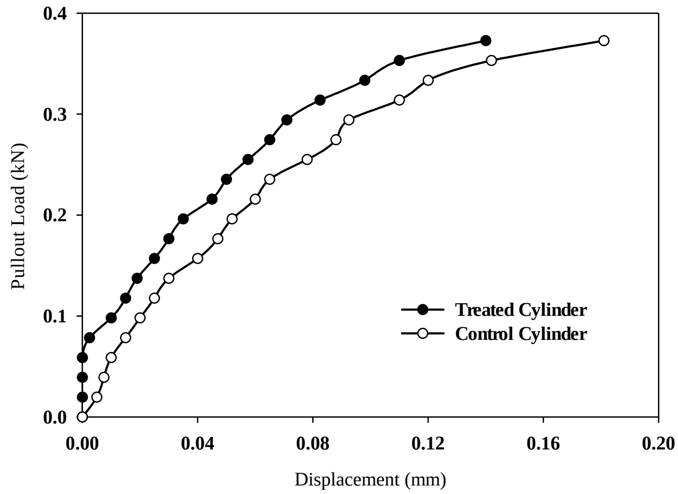


Table 4. Shear strength and water content of the soil after the second phase of treatment.

	Control cylinder		Treated cylinder		Difference	
Depth (m)	Shear strength c_u (kPa)	Water content w (%)	Shear strength c_u (kPa)	Water content w (%)	Δc_u (kPa)	Δw (%)
Location 1						
0.3	5.80	41.00	5.5	41.27	–0.32	0.27
0.6	7.00	40.00	8.25	39.70	1.25	–0.30
0.9	9.10	40.16	11.20	40.40	2.10	–0.24
Average	7.30	40.38	8.32	40.46	1.02	0.08
Location 2						
0.3	6.2	40.37	6.2	42.14	0.00	1.77
0.6	7.60	40.48	8.00	41.59	0.40	1.11
0.9	9.6	40.98	12.00	39.40	2.40	–1.15
Average	7.8	40.61	8.73	41.04	0.57	0.43
Location 3						
0.3	5.00	41.17	6.00	39.35	1.00	–1.83
0.6	8.3	40.16	12.2	41.69	3.90	1.53
0.9	9.2	39.19	18.25	38.50	9.05	–0.69
Average	7.50	40.17	12.15	39.85	4.65	–1.32

and the pile shaft had increased after applying the high voltage and (or) an increase in shear strength had occurred close to the piles. This increase could not be detected by the vane tester.

Treatment effect on pullout pile capacity

The load was applied incrementally with a constant time interval of 2.5 min. A load increment of 19.6 N (2.0 kg) was maintained throughout the test. The load–displacement relationship obtained is shown in Fig. 11.

Both piles exhibited different behaviour from the early loading stages. The pile in the control cylinder displayed a softer response during the entire loading test. The failure criterion used to determine the pullout capacity is reported by Prakash and Sharma (1990). In this failure criterion, the upward failure was at the point of intersection of tangents on the load–displacement curve. The failure load for the pile in the control cylinder was 0.27 kN. The pile in the treated cylinder displayed negligible displacement at earlier loading increments, indicating that the soil stiffness in the vicinity of the pile had increased. The failure load for the pile in the treated cylinder was 0.30 kN, an increase of about 11.0%.

High-voltage application (phase 2)

In the second phase of this study, a –30 kV dc voltage of negative polarity was applied to the treatment cylinder for 33 days. The negative high voltage was applied to the outer electrodes continuously during the test period. A short circuit between the high-voltage electrode and the grounded electrode caused by a defect in the insulation resulted in an overload and shut off the power supply at the initial stage of the voltage application. The insulation was then strengthened by removing the damaged part of the tube and adding another insulation layer. Furthermore, the seal at the end of

Fig. 12. Shear strength after the second treatment phase.

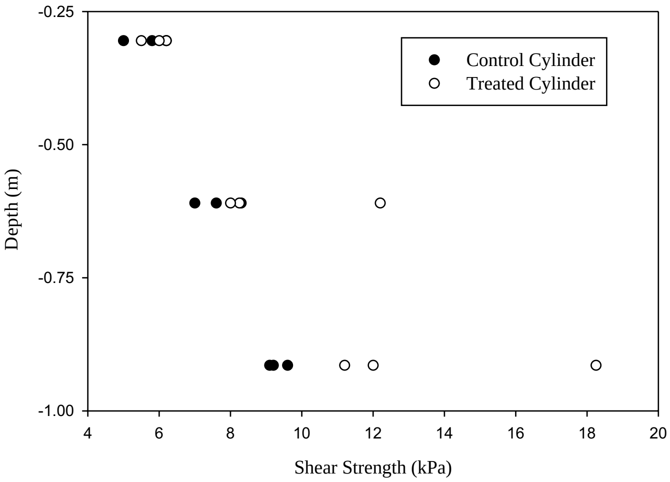
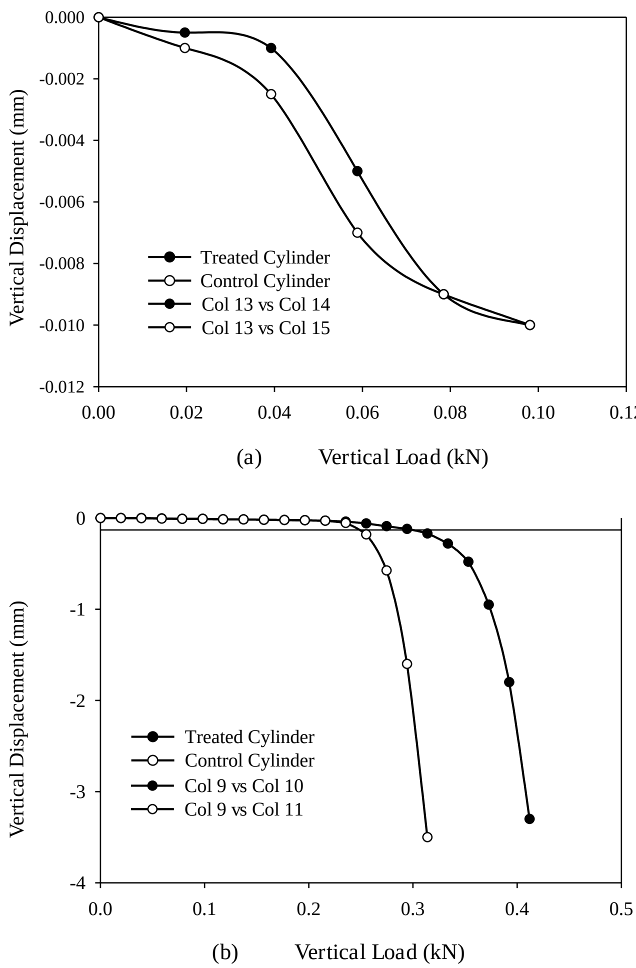
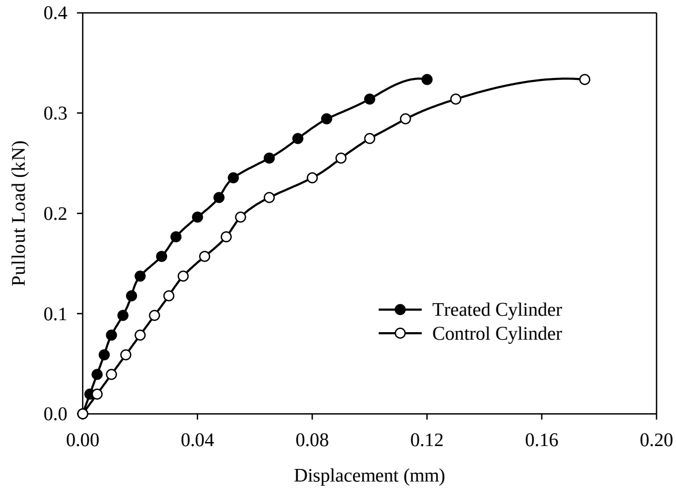


Fig. 13. Axial load – displacement curve after the second treatment phase: (*a*) at the initial loading increments; (*b*) loading to failure.



the damaged electrode was replaced and a piece of adhesive shrinkable tubing was used to protect the Silicon insulation during the electrode installation.

Fig. 14. Pullout resistance of piles after the second treatment phase.



The high voltage was turned off at the end of treatment and a series of soil and pile tests was carried out for the same piles in both cylinders.

Treatment effect on soil properties

The water content and shear strength were measured at different points in three layers in the cylinders. The undrained shear strength and water content of the soil (at the locations of measurement) in the treated and control cylinders are summarized in Table 4. The shear strength results at each layer in the treated and control cylinders are shown in Fig. 12.

The increase in shear strength is evident despite a rather large deviation in the results. The average undrained shear strength at the treated cylinder (at the locations of measurement) increased by about 27%, and the average water content was found to be almost the same at both cylinders as shown in Table 4. Further, it was noted that the shear strength increased with depth, with the maximum difference at a depth of 0.90 m from the soil surface. No soil settlement was observed at this treatment phase, which is consistent with the results of the soil water content.

Treatment effect on axial pile capacity

In the early loading increments, the pile in the treated cylinder displayed a stiffer response than the pile in the control cylinder as shown in Fig. 13*a*. This behaviour indicates that the soil stiffness in the vicinity of the pile had increased. For an applied load of up to 0.2 kN, both piles behaved the same, with the displacement increasing almost linearly with the load. Afterwards, strong nonlinear behaviour was observed and the pile in the control cylinder failed when a load of 0.23 kN was reached as shown in Fig. 13*b*. However, the pile in the treated cylinder resisted a load up to 0.32 kN and started gradually to present excessive settlement. The capacity of the pile in the treated and control cylinders was 0.36 and 0.28 kN, respectively, increases of about 29%.

Treatment effect on pullout pile capacity

Figure 14 shows that both piles exhibited different behaviour in earlier loading increments. The pile in the control cylinder displayed a softer response during the entire load-

Table 5. Shear strength and water content of the soil after the third phase of treatment.

	Control cylinder		Treated cylinder		Difference	
Depth (m)	Shear strength c_u (kPa)	Water content w (%)	Shear strength c_u (kPa)	Water content w (%)	Δc_u (kPa)	Δw (%)
Location 1						
0.3	6.30	41.00	7.5	40.27	1.20	–0.73
0.6	10.50	40.10	10.50	40.50	0.00	0.40
0.9	10.60	40.16	16.00	39.40	5.40	–0.76
Average	9.13	40.42	11.33	40.06	2.20	–0.36
Location 2						
0.3	6.50	40.37	6.50	41.14	0.00	0.77
0.6	7.60	40.38	17.00	39.39	9.40	–0.99
0.9	6.5	40.08	12.00	39.40	5.50	–0.68
Average	6.86	40.27	11.83	39.97	4.97	–0.30
Location 3						
0.3	3.50	41.81	9.50	40.99	6.00	–0.82
0.6	10.00	40.17	13.50	39.69	3.50	–0.48
0.9	10.50	39.19	13.00	38.30	2.50	–0.89
Average	8.00	40.39	12.00	39.66	4.00	–0.73

Fig. 15. Shear strength after the third treatment phase.

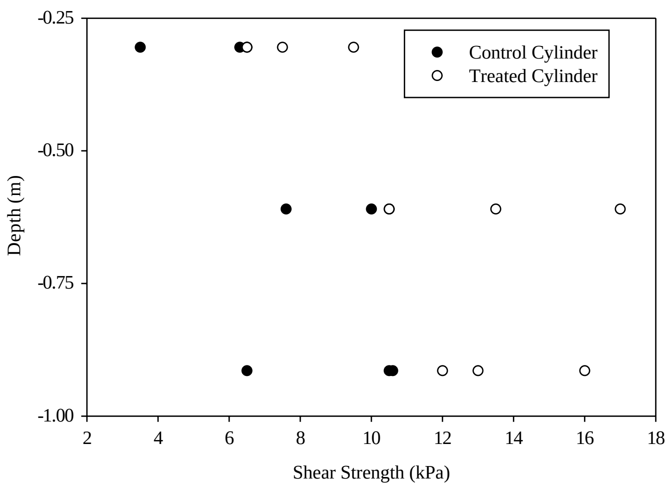
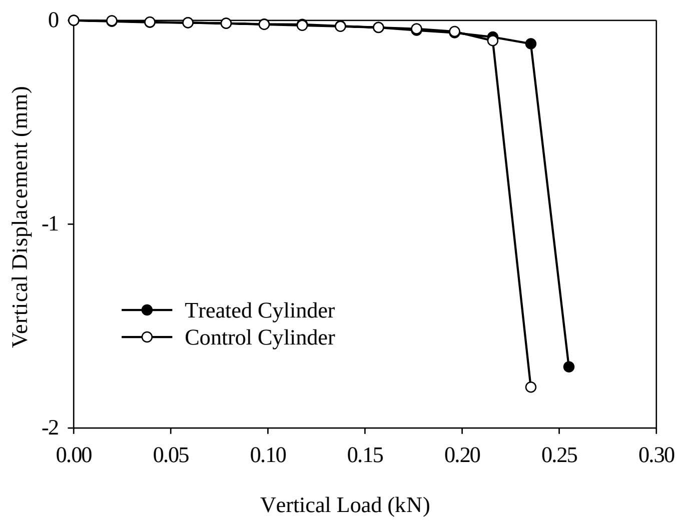


Fig. 16. Axial load – displacement curve after the third treatment phase.



ing test. The failure loads for the pile in the control and treated cylinders were 0.24 and 0.295 kN, respectively, increases of about 23%.

High-voltage application (phase 3)

A –10 kV dc voltage was applied to the treatment cylinder in the third phase of this study for the same time period using the same configuration and setup discussed earlier. The negative high voltage was applied to the outer electrodes continuously during the test period. The Teflon insulation was strong enough to resist the applied voltage without being damaged.

After treatment, the high voltage was turned off and a series of soil and pile tests was carried out for the same piles in both cylinders.

Treatment effect on soil properties

The water content and shear strength were measured at different points in three layers in the cylinders. The undrained shear strength and water content of the soil (at the locations of measurement) in the treated and control cylinders are summarized in Table 5. The shear strength results at each layer in the treated and control cylinders are shown in Fig. 15. The average undrained shear strength in the treated cylinder (at the locations of measurement) had increased about 46% and the average water content was found to be almost the same in both cylinders. In addition, the shear strength increased with depth and the maximum difference was observed at a depth of 0.90 m from the soil surface. Negligible soil settlement was observed at this treatment phase, which was consistent with the decrease in soil water content.

Treatment effect on axial pile capacity

Figure 16 shows that both piles behaved the same up to an applied load of 0.2 kN, the displacement increasing almost

Fig. 17. Pullout resistance of piles after the third treatment phase.

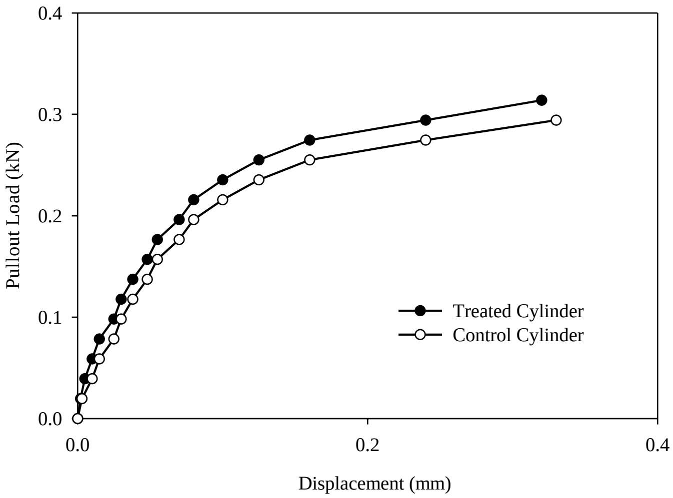


Fig. 18. Relationship between the normalized voltage and the percent increase in the axial capacity of the piles.

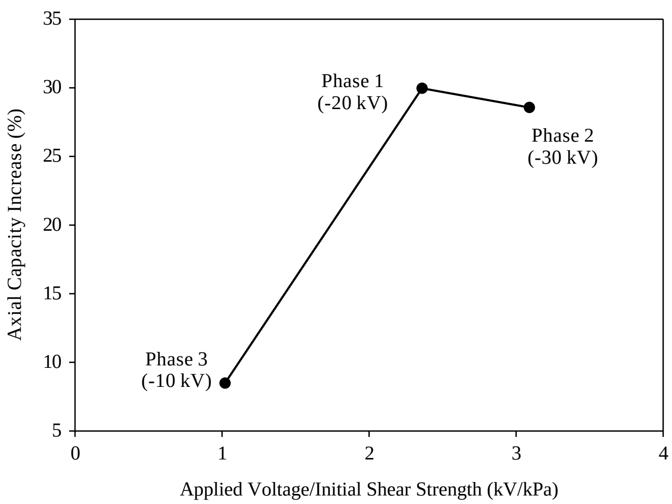


Fig. 19. Relationship between the normalized voltage and the percent increase in the pullout capacity of the piles.

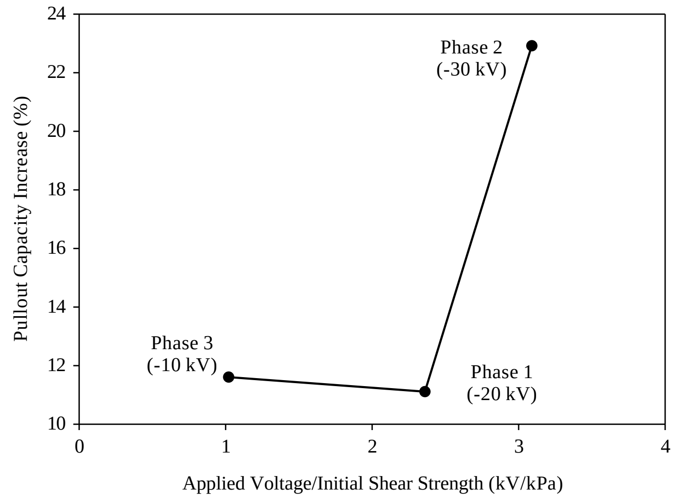
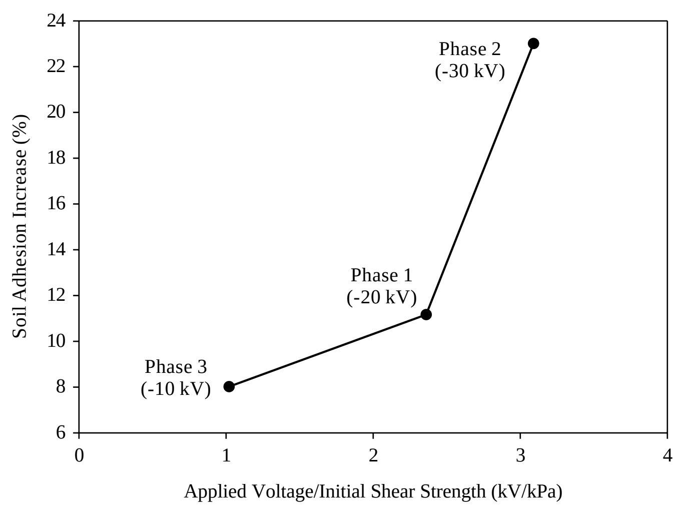


Fig. 20. Relationship between the normalized voltage and the percent increase in soil adhesion.



linearly with load until a load of 0.22 kN was reached. Afterwards, the pile in the control cylinder displayed a strong nonlinearity and failed. However, the pile in the treated cylinder had sustained a load of 0.24 kN and then went through excessive settlement. The pile capacity in the treated and control cylinders was 0.243 and 0.224 kN, respectively, with an increase of about 8% after applying the third phase of the treatment.

Treatment effect on pullout pile capacity

The load–displacement relationship is shown in Fig. 17. Both piles exhibited behaviour different from that of the earlier loading increments. The pile in the control cylinder displayed a larger displacement during the loading test until failure occurred. The failure loads for the pile in the control and treated cylinders were 0.224 and 0.25 kN, respectively, increases of about 11.6%.

Discussion

The average undrained shear strength c_u of the soil increased 8, 29, and 46% at the location of measurements in the treated cylinder after applying the first, second, and third treatment phases, respectively. The percent increase was calculated as follows:

$$\text{percent increase} = \frac{c_u(\text{treated}) - c_u(\text{control})}{c_u(\text{control})}$$

A negligible change in the soil water content was observed, and no significant soil settlement was measured during the three phases of treatment.

The initial shear strength of the soil in the control cylinder was different from that in the treated cylinder, especially for the second and third treatment phases. To account for the initial soil condition at each treatment phase, the applied voltage could be normalized by the measured initial undrained shear strength. Figure 18 presents the relationship between the normalized voltage and the percent increase in axial capacity of the piles which was calculated according to the following relation:

$$\text{percent increase} = \frac{(Q)_t - (Q)_c}{(Q)_c} 100$$

where $(Q)_t$ is the capacity of the pile in the treated cylinder, and $(Q)_c$ is the capacity of pile in the control cylinder.

Figure 18 shows that by increasing the applied voltage from –10 to –30 kV the axial capacity of the piles in the treated cylinder significantly increased from about 8 to 30%, and the major influence was observed at the first phase of treatment using a voltage of –20 kV. Similarly, the percent increase in the pullout capacity of the piles was plotted for each phase of treatment against the normalized voltage, and the results are presented in Fig. 19. The maximum pullout capacity was recorded at the second treatment phase, where a voltage of –30 kV was used. However, at the first and third treatment phases, with applied voltages of –20 and –10 kV, respectively, the increase in the pullout capacity of the piles was almost the same. This behaviour could be explained as an increase in the soil adhesion at the pile–soil interface due to the applied voltage.

The decrease in the pullout resistance after the third phase of treatment may be attributed to the fact that the soil adhesion along the exterior wall of the shaft was substantially decreased due to the clay remolding, as failure occurred in the second loading test and the treatment effort was not enough to regain the strength (10 kV voltage only). A similar observation was made by Shang and Dunlap (1996, 1998). They conducted a series of pullout tests for aluminum tubes embedded in marine sediment and subjected to high voltages of –15, –10, and –30 kV, respectively. The results showed a decrease in the pullout resistance after treatment in all three tests. It was observed that a clay film was sticking to the outer perimeter of the piles reducing the pile shaft resistance.

The soil adhesion, αc_u, was also plotted against the normalized voltage in Fig. 20. Since the pullout pile capacity was directly proportional to the soil adhesion, the same behaviour was noticed. As the applied voltage increased, the soil adhesion increased, and maximum improvement was observed at the third treatment phase.

Summary and conclusions

A large-scale testing facility was designed and fabricated to investigate the effect of high-voltage electrical treatment on soil and pile behaviour. This facility included two steel cylinders. One cylinder was used to implement the treatment and the other was used as a control to compensate for the effect of natural aging and drying of soil.

Negative high voltages of –20, –30, and –10 kV were applied for 33 days in the treatment cylinder. The axial and pullout tests of piles were performed and the results were compared for both cylinders after each phase of treatment. The axial capacity was increased 30, 29, and 8% after applying –20, –30, and –10 kV, respectively. Furthermore, the soil adhesion factor, αc_u, was backcalculated from the results of the experimental tests and found to have increased 11, 23, and 8% after applying –20, –30, and –10 kV, respectively. The backcalculated adhesion factor, α, was considerably lower than the value suggested in the literature for similar undrained shear strengths.

The high-voltage treatment could be used to accelerate the restoration process of the capacity of the piles after disturbance due to storm loading conditions.

Acknowledgments

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