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# Increasing pullout resistance of offshore foundations in soft clays

## Augmentation de la résistance à l'arrachement des fondations marines dans des argiles molles

S. Micic
*Trow Associates Inc., Brampton, Canada*
K.Y. Lo
*Geotechnical Research Centre, University of Western Ontario, Canada*

ABSTRACT

The paper presents the results of the large-scale laboratory tests conducted on the electrokinetic strengthening of natural marine clay for offshore foundations. A steel cylinder, 200 mm in diameter and 400 mm in length, was adopted as the model of foundation element and it was equipped with eight electrodes equally spaced around the outside wall of the cylinder. Attaching the electrodes on the cylinder with the holding ring facilitated the one-pass installation procedure, so that the cylinder and electrodes could be installed simultaneously. A dc voltage of 5.2 V with polarity reversal was applied over a period of 28 days. A control test with identical configuration to that of the electrokinetic treatment test was also set up to provide baseline data. After the treatment pullout tests were performed on both cylinders and the effect of electrokinetics was evaluated. The results demonstrated that the pullout resistance of the foundation model embedded in natural marine clay increased up to 5 times, after the electrokinetic treatment, as compared with that of the control without treatment. The clay adhered strongly to the cylinder and electrodes, indicating bonding was developed between soil and steel after the treatment. The XRF analysis showed significant increase of iron oxide after the treatment, which is known as a cementation agent in soils. The electrokinetic treatment also accelerated the recovery of friction resistance of the foundation after subjected to failure.

RÉSUMÉ

Cet article présente les resultats d'essais à échelle réelle du renforcement électrocinétique de l'argile marine naturelle à l'égard des fondations marines. Un cylindre en acier, d'un diamètre de 200 mm et d'une longueur de 400 mm, servit comme modèle d'élément de fondation. Huit électrodes furent fixées à distances égales autour de l'extérieur du cylindre. Il fut possible d'installer simultanément le cylindre et les électrodes grâce au mécanisme de fixation. Un courant continu, à polarité inverse, d'une tension de 5,2V, fut appliqué pendant une période de 28 jours. Un essai témoin ayant la même configuration que l'essai du traitement électrocinétique fournit les données de reference. Une fois le traitement électrocinétique achevé, des essais d'arrachement furent éffectués sur les deux cylindres et l'effet de l'application électrocinétique fut évalué. Les résultats démontrent une augmentation de jusqu'à cinq fois de la résistance à l'arrachement du modèle de fondation enfoncée dans l'argile marine naturelle après le traitement électrocinétique par rapport à l'essai témoin qui ne subit aucun traitement. L'argile tenait fortement au cylindre et aux electrodes, indicant la production d'une adhesion entre le sol et l'acier lors du traitement. L'analyse XRF indique une augmentation importante d'oxyde ferrique, un agent de cementation de sols reconnu, suite au traitement. Le traitement électrocinétique accéléra aussi le rétablissement de la résistance au frottement de la fondation suite à une rupture.

## 1 INTRODUCTION

The exploration of oil and gas reserves of offshore fields has resulted in construction of many different types of platforms whose design and installation greatly depend on the foundation soils. Very often these structures have to be founded on soft marine clay deposits characterized by the low shear strength and high compressibility dictating very expensive foundation solutions. Electrokinetics as a ground improvement technique has been applied in projects for strengthening of pile foundations in soils of low pore fluid salinity (e.g. Soderman and Milligan, 1961). It has been shown that the effect of strengthening is permanent (Milligan, 1994). Therefore, electrokinetics may possess the potential to increase the load-carrying capacity of the offshore platform foundations such as steel caissons and piles reducing the cost of the foundations.

The strengthening of soft marine clay with high pore fluid salinity by using electrokinetics has been studied in recent years (Lo et al. 2000). Micic et al. (2003) first studied the improvement of installation and performance of offshore foundation elements in clayey marine soil by using electrokinetics. In their study, the low dc voltage was applied via steel electrodes installed independently inside and outside the foundation models embedded in simulated marine clay. The results of compression loading tests showed the load-carrying capacity of the offshore foundation model increased by as much as three-fold after electrokinetic treatment. The results of pullout loading tests performed on the foundation model after its failure and subsequent electrokinetic treatment indicated 150 % failure-recovery for the pullout resistance due to electrokinetic treatment. The primary mechanism of strengthening is the improvement of adhesion between the soil and embedded foundation in addition to strength increase in the host clay mass. The improvement was mostly attributed to electro-cementation of soil particles and bonding between soil solids and the steel objects by cementing agents such as iron oxides and carbonates.

The present study is focused on development an in-situ practical design methodology of using electrokinetics for increasing the load-carrying capacities of offshore foundations embedded in soft marine deposits. Since the dominant component of load carrying capacity for offshore foundations is the frictional resistance along the shaft, the enhancement process focused on the soil-foundation interface. The electrode configuration and installation procedure were improved in this research comparing to the previous in order to develop the electrokinetic strengthening as a more effective and practical ground improvement technology for offshore engineering practice. Electrokinetic tests were carried out on foundation models embedded in natural marine clay placed in a large model tank. The foundation model consisted of the steel cylinder and eight electrodes attached on the cylinder with a specially designed spacer ring, so the cylinder and electrodes could be installed simultaneously making the process of installation much more practical. The electrodes were placed close to the cylinder, spaced equally around its outside wall in order to create the effective electric field for strengthening of the soil-foundation interface. A low voltage dc electric field was applied for 28 days. After the treatment the pullout tests were performed on the treated and control foundation models, and the effect of electrokinetics was evaluated through changes in pullout resistance after the treatment. After the pullout tests, the control cylinder was pushed back into the soil sample and it was subjected to the electrokinetic treatment to study the effect of the treatment on the foundation post-failure recovery.

Table 1. Summary of soil properties

| Soil Properties | |
|---|---|
| *Bulk natural soil* | |
| Liquid limit, *%* | 61.5 |
| Plastic limit, *%* | 34.2 |
| Plasticity index | 27.3 |
| Sand, *%* | 10 |
| Silt, *%* | 45 |
| Clay, *%* | 45 |
| Specific gravity ($G_s$) | 2.73 |
| *Bulk soil (< 76 μm fraction)* | |
| CEC, *meq/100 g soil* | 6.7 |
| Specific surface, $m^2/g$ *soil* | 23 |
| Carbonate content, *%* | ~0 |
| Iron oxide ($Fe_2O_3$), *%* | 5.74 |
| *Mineralogy* | |
| Illite, *%* | ~41.4 |
| Kaolinite, *%* | ~38 |
| Vermiculite, *%* | <5 |
| Quartz, *%* | ~10 |
| Feldspar, *%* | ~2 |
| *Pore water* | |
| Salinity, *g NaCl/l* | 53 |
| Electrical conductivity, *S/m* | 6 |
| pH | 7.5 |
| Concentration of | |
| $Na^+$, *ppm* | 16834 |
| $Ca^{2+}$, *ppm* | 1378 |
| $K^+$, *ppm* | 716 |
| $Mg^{2+}$, *ppm* | 2354 |
| $Fe^{2+}$and $Fe^{3+}$, *ppm* | 0 |
| $SO_4^{2-}$, *ppm* | 6750 |
| $Cl^-$, *ppm* | 28402 |
| $HCO_3^-$, *ppm* | 140 |

## 2 MARINE SOIL TESTED

The marine soil dredged from the surface of seabed at Yulchon, South Korea, was used in this study. The soil is characterized as a dark grey silty clay with 10 % sand-, 45 % silt-, and 45 % clay-sized grains. The dominant clay minerals are illite and kaolinite, while quartz is the major nonclay mineral. The salinity of pore water was 53 g/*l* deduced from electrical conductivity measurements and expressed in equivalent grams of NaCl per litre of water. The main cations and anions in the pore water are sodium and chloride. The electrical conductivity of the Yulchon clay was measured using the ASTM procedures G57-95a (ASTM, 1995) and found to be 1.15 S/m. The summary of the properties of the Yulchon soil is presented in Table 1.

## 3 TESTING FACILITY

Figure 1 shows schematically the testing facility, which included a model tank, loading equipment, foundation model with attached electrodes and electrical system.

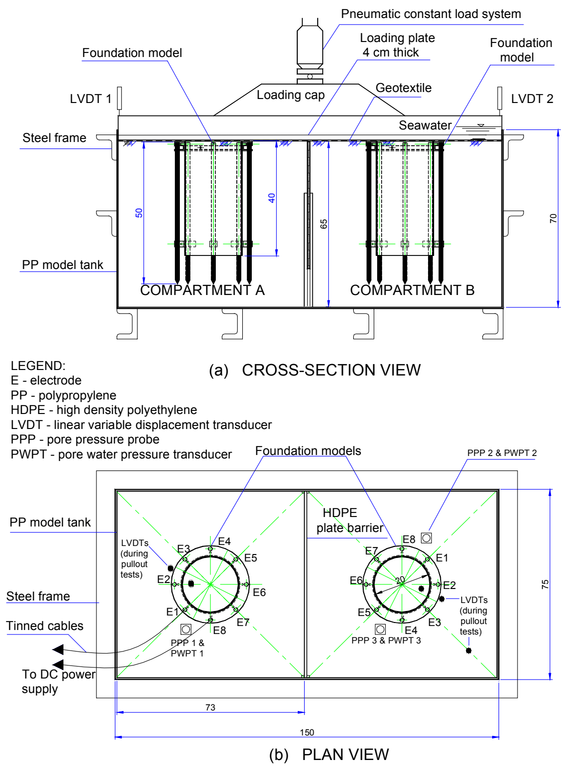



Figure 1. Schematic of model tank (all dimensions in cm)

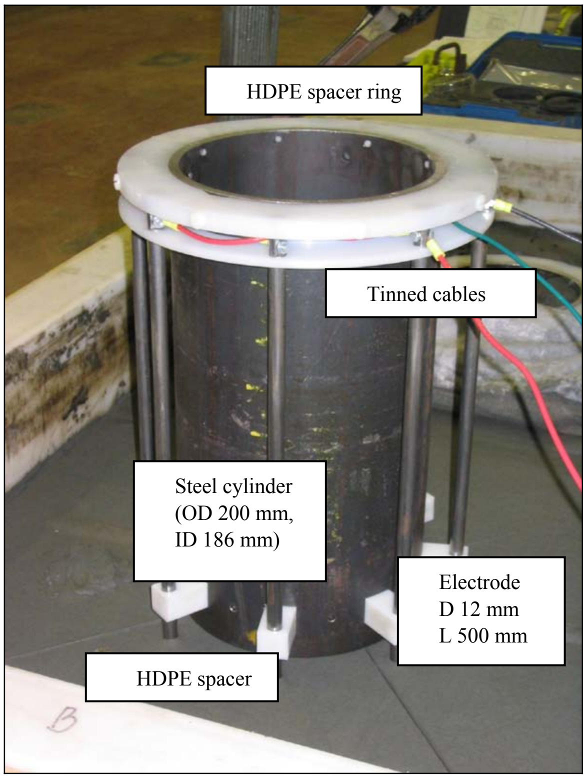



Figure 2. Foundation model

The model tank was made of polypropylene with dimensions of 150 cm long, 75 cm wide and 70 cm high. It is reinforced on the outside by a steel frame. The tank is divided by a plastic plate into two identical compartments named Compartment A and B. Compartment A was utilized for the first EK test (EK Test 1), while Compartment B was used for the control test, which provides baseline data without the treatment. Compartment B was employed later for the second EK test (EK Test 2).

The loading equipment consisted of a loading cap and pneumatic constant load system, as shown in Figure 1. It served to apply overburden pressure of 15 kPa on the soil, which simulated the in-situ stress condition. The loading plate was made of electrically insulating polypropylene. To provide uniform vertical pressure on the soil sample the plate was designed to have the dimensions slightly smaller then the horizontal cross-section area of the tank. It was perforated to allow the excess pore water to dissipate during the soil consolidation and also to maintain the submerged condition during the testing periods.

Figure 2 shows the foundation model used in this study. A 400-mm long steel cylinder with an outside diameter of 200 mm and wall thickness of 8.3 mm was adopted as the model of foundation element and it was equipped with eight electrodes. The electrodes were made of solid steel rods of 12 mm diameter and 500 mm length. They were attached to the cylinder with a specially designed plastic spacer ring and spacers as shown in Figure 2. The ring was mounted to the top of the cylinder by Teflon screws. The ring provided the spacing between the electrode and the wall of the cylinder of 30 mm and secured the cables used to connect electrodes. The electrodes were arranged equally spaced around the cylinder to generate an electrokinetic field in the soil outside of the cylinder. A plan view of the electrode layout is shown in Figure 1. The electrodes were installed close to the cylinder to maximize the effectiveness of electrokinetic strengthening around the foundation.

A dc power supply (AT/6012B) having capacity of 1000 W with maximum ratings of 60 V and 50 A was used in the tests. The wiring between electrodes and power supply was made through tinned copper terminals and AWG 10 tinned copper wires for maximum corrosion protection. The electrode-wire connection was covered with a layer of silicon sealant as an insulator to provide greater salt water and chemical resistance.

## 4 TESTING PROCEDURE

The experimental program of this study included two electrokinetic tests named EK Test 1 and EK Test 2. EK Test 1 was conducted in Compartment A after the foundation models were installed in the already consolidated soil. Compartment B served for the control test. EK Test 1 was performed to study the effect of electrokinetic treatment on the pullout resistance of the foundation model embedded in natural marine clay. EK Test 2 was carried out in Compartment B after the pullout test on the control cylinder. After the pullout test the control cylinder was pushed back into the soil sample and subjected to the electrokinetic treatment. EK Test 2 was designed to study the effect of the treatment on the foundation post-failure recovery.

After filling both compartments of the model tank with the Yulchon soil up to 65 cm height, a geotextile was placed on top of the soil as a drainage layer. A perforated plastic loading plate was then placed for applying a constant consolidation pressure of 15 kPa. During the consolidation the settlement and pore pressure were monitored. The consolidation of the soil lasted approximately 90 days. After the soil was consolidated, the sample was unloaded and a foundation model was installed in the centre of each compartment. The foundation models were pushed slowly into the soil by a pneumatic load piston. After the foundation modes were installed, the geotextile and loading plate were placed again on the top of the soil and a pressure of

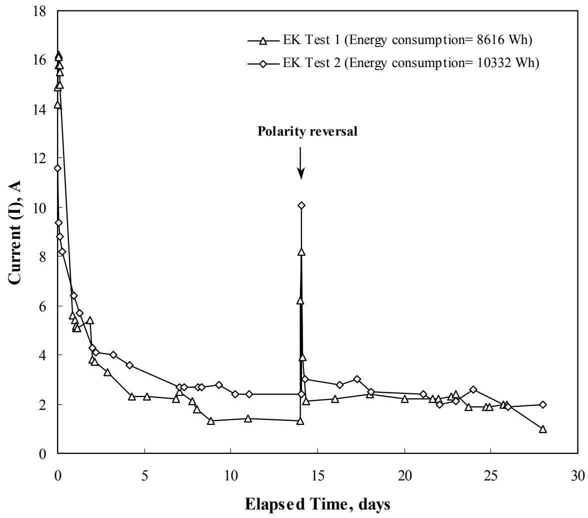



Figure 3. Electric current vs. elapsed time

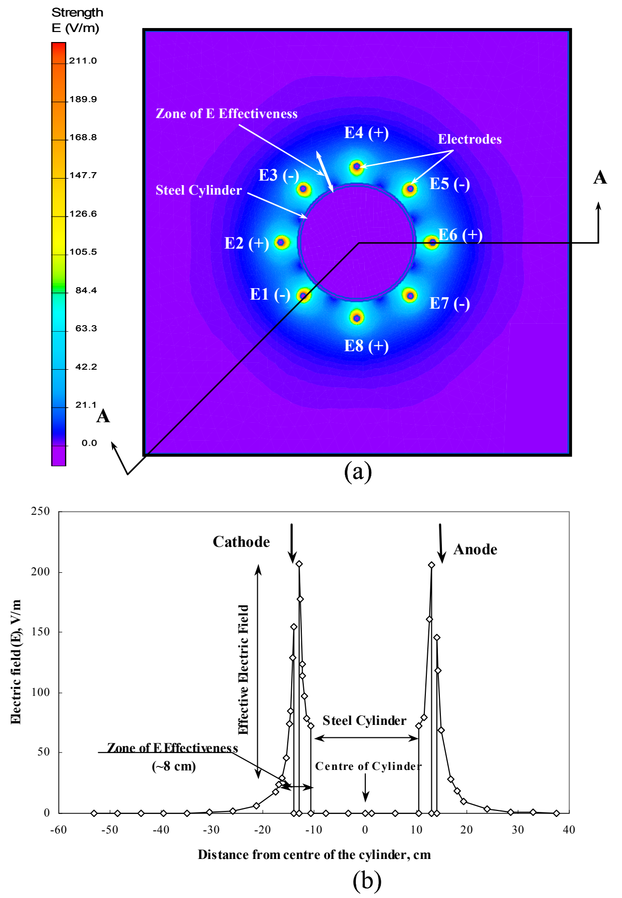



Figure 4. Distribution of electric field intensity in the tank: (a) Plan view of electric field; and (b) Electric field along cross-section A-A

15 kPa was re-applied. Submerged condition was ensured during the electrokinetic treatments.

In the first electrokinetic test (EK Test 1) the soil around the foundation model in Compartment A was treated applying a dc voltage of 5.2 V for 28 days. In the first 14 days of electrokinetic treatment electrodes E1, E3, E5 and E7 served as the anodes and E2, E4, E6 and E8 as the cathodes. The polarity of the electrode was reversed on the 14$^{th}$ day of the treatment. The cylinder was connected to the ground. Figure 3 shows the electric current versus the elapsed time, while Figure 4 shows the distribution of electric field intensity around the cylinder. After the completion of EK Test 1, a pullout test was performed on both foundation models embedded in Compartments A and B using a MTS machine at a constant displacement rate of 0.5 mm/min. This rate simulated undrained failure condition. The pullout loads and vertical displacements of the foundation model and soil around the cylinder were measured using a 40 kN load cell and linear variable displacement transducers (LVDT), respectively, connected to a data acquisition system.

After pullout tests, the control cylinder was push back quickly to its original position, and a surcharge of 15 kPa was applied. Then, the second electrokinetic treatment (EK Test 2) around that cylinder was commenced under the same electrical conditions as those in EK Test 1. EK Test 2 was also terminated after 28 days. The changes in the electric current during EK Test 2 are shown on Figure 3. The same current behavior was observed in both EK tests. The current decreased gradually throughout treatment what is typical in all aqueous electrolyte systems (Russell et al., 1989). The energy consumptions in EK Test 1 and EK Test 2 were estimated to be 8616 Wh and 10332 Wh, respectively. After EK Test 2, the loading plate was removed and the pullout test was conducted again. In addition, the post-treatment tests such as water content and undrained shear strength measurements, soil chemistry analyses (XRF, specific surface and cation exchange capacity) and scanning electron microscopy tests were conducted on the soil samples.

## 5 RESULTS AND DISCUSSION

The pullout tests were performed on the cylinders embedded in Compartments A and B (control) after EK Test 1. Figure 5 shows the load-displacement relationships. The pullout resistance at failure $Q_f$ is defined as the point of intersection of tangents on the both sides of the sharp bend of the load-displacement curve (Prakash and Sharma, 1990). As shown on the figure the pullout resistance at failure of the control test $Q_f$ is 3.2 kN. The figure also shows that after EK Test 1 the pullout resistance at failure $Q_{f,e}$ is 15.8 kN, indicating five fold increase in the pullout resistance due to electrokinetic treatment. Both load-displacement curves exhibited similar behaviour before and after the failure. At the beginning of the loading the load-displacement response is approximately liner until failure occurred at approximately 3 mm and 4 mm in the control and EK Test 1, respectively. The gradient of the pullout load versus displacement is much higher after EK Test 1 than in the control test, indicating the development of the interface bonding between the soil and steel cylinder in the former case because of electrokinetic treatment. The post-failure load-displacement curves show the strain softening behaviour in both cases. However, the post-peak pullout resistance at large displacements of the cylinder embedded in the electrokinetically treated soil is approximately 250 % greater than that of the cylinder embedded in the untreated soil.

After failure, the cylinder in Compartment B (control test) was pushed back to its original position and EK Test 2 was commenced. EK Test 2 was followed by a pullout test to study the effect of electrokinetic treatment on the foundation remedy after failure. The results are presented in Figure 5. The figure shows that the load-displacement curves after EK Test 2 and EK Test 1 are similar. The pullout resistance at the failure is 15.8 kN and the displacement is 5 mm. The results clearly show that electrokinetic treatment not only accelerated the recovery of the foundation element previously subjected to large deformation or failure, but also further significantly increased its pullout resistance.

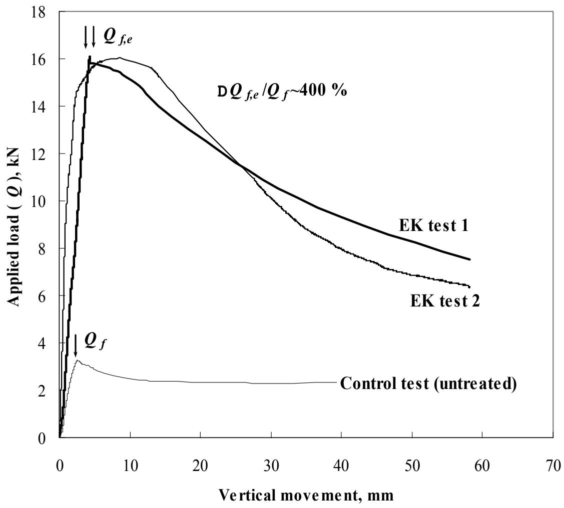
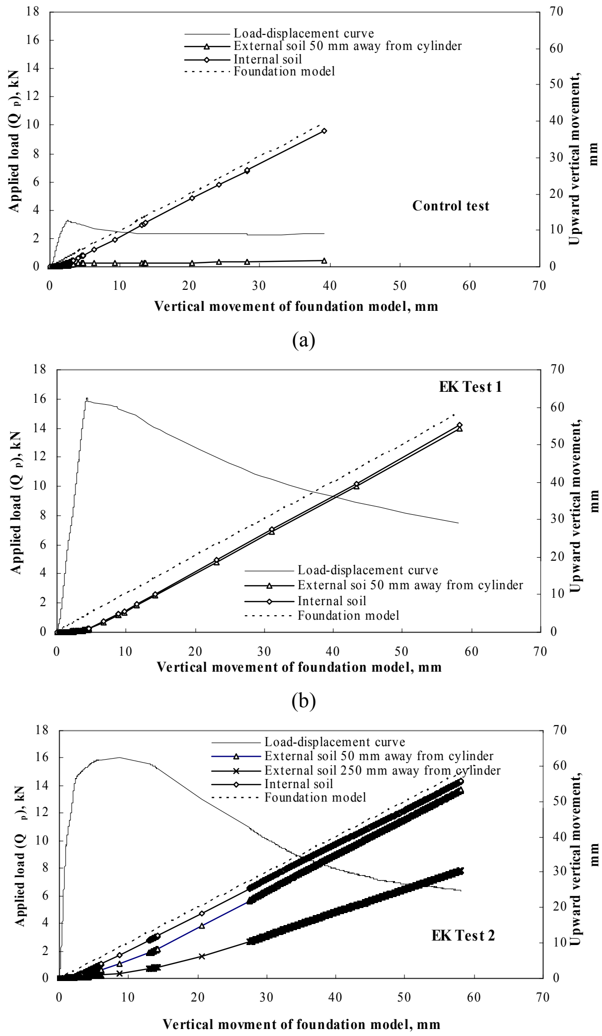



Figure 5. Results of pullout tests




(c)

Figure 6. Vertical movement of cylinders and soils around cylinders during the pullout tests: (a) Control test; (b) EK Test 1; and (c) EK Test 2

Another important effect of the electrokinetic treatment observed during the pullout tests is upward movement of the soil enclosed to the cylinder. The displacement of the soil is recorded by LVDTs installed around the cylinder. Figure 6 (a) shows the results of the displacement behaviour of the soil inside and outside the cylinder during the pullout test performed in the control compartment (Compartment B). It is evident that the soil plug was formed and moved upwards together with the control cylinder, while no soil movement was recorded outside the cylinder indicating displacements were predominately occurring at or close to the soil/steel outer interface. The instrumentation clearly shows that the soil plug inside the cylinder did not slip during the pullout test. Figures 6 (b) and (c) present the upward movement of the soil around the cylinder after EK Test 1 and EK Test 2, respectively. In both cases it is evident that the soil inside and outside the cylinders displaced identically with the cylinder during the entire pullout process. Actually the whole block of the soil in the compartment was observed to be pullout together with cylinder. Figure 6 (c) shows that the LVDT placed 250 mm (2.5 times the radius of the cylinder) away from the cylinder recorded the upward movement of the soil during the pullout test. The drastic change of displacement mechanism contributes to the large increase in pullout capacity.

In the control and treated cases, the pullout load is resisted by the skin friction between the soil and outer wall of the cylinder and the weights of the cylinder and soil plug inside. Since the weight of the cylinder, the weight of the soil plug inside the cylinder and the external area of the cylinder in contact with the soil are the same in the control and treated cases, the increase in the pullout resistance after the electrokinetic treatment of approximately 400 % can be attributed to increase in the skin friction between the outside wall of the cylinder and the soil.

After the completion of EK Test 2 the cylinders were extracted from the treated soil. Figure 7 shows the cylinder during its extraction. As can be seen from the figure, a soil layer of approximately 80 mm was firmly attached to the foundation system and pull out together with the cylinder. According to Figure 4 it is a zone where the created electric field was the strongest during the treatment (E = 25-200 V/m). The soil attached on the cylinder and electrodes was cemented and very firm. It is evident that bonding between soil solids and the steel objects as well as between soil particles was developed due to electrokinetic treatment. Formation of this soil layer significantly improved the skin friction between the soil and foundation, and thus, increased the pullout resistance of the foundation.

The water content test results are listed in Table 2. The results show that the water content decreased from 61.3 % to the average of 53.4 % in the soil close to the cylinder or electrodes due to electrokinetic treatment. In addition, the vane shear tests were performed in the soil below the cylinder after its extraction to measure the undrained shear strength of the 100-mm thick soil layer below the cylinder tip, which was electrokinetically treated since the electrodes were 100 mm longer than the cylinder. The average results are presented in Table 2. It is evident that the undrained shear strength of the soil at the bottom of the cylinder tip increased significantly after electrokinetic treatment. The average shear strength of the treated soil at the measurement locations was 52.5 kPa compared to 13.5 kPa measured in the control test, indicating an increase due to electrokinetics of approximately 290 %.

The measured pullout resistance $Q_f$ in the control test can be correlated empirically with the average undrained shear strength of the untreated Yulchon clay $c_u$ ($c_u$=13.5 kPa) because it represents the undisturbed natural clay over the depth occupied by the cylinder, i.e.,

$$Q_f = a c_u A_o + W_c + W_s \quad (1)$$

where a = adhesion coefficient; $A_o$ = external area of cylinder in contact with soil ($A_o$=0.25 m$^2$); $W_c$ = weight of cylinder ($W_c$=0.14 kN); $Ws$ = weight of soil plug inside the cylinder ($W_s$=0.08 kN).

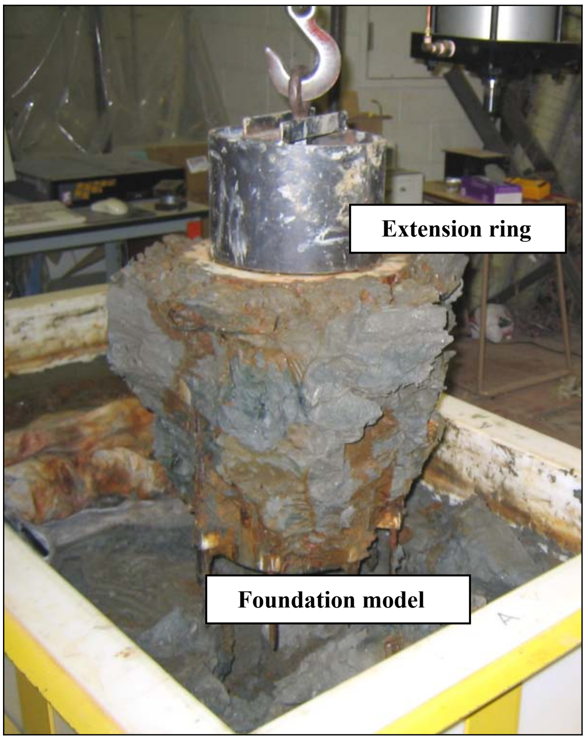
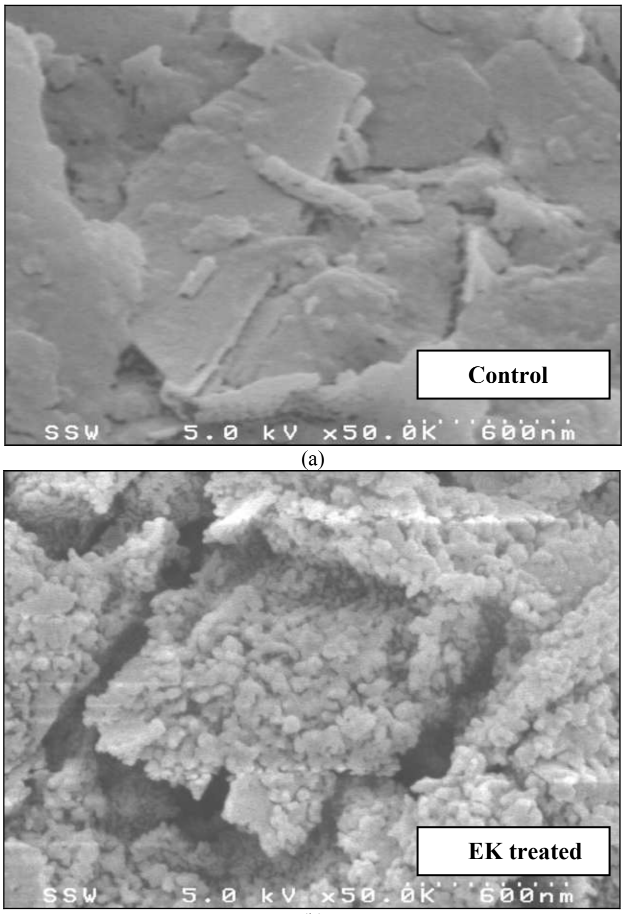



Figure 7. The foundation model during its excavation




(a)

(b)

Figure 8. Electron microscopy images of Yulchon clay: (a) Control samples; (b) EK treated samples

Table 2. Summary results of the post-treatment tests conducted

| | Control | After EK Treatment | | | |
|---|---|---|---|---|---|
| | | Inside Cylinder | Between Electrodes | Between Electrode and Cylinder | Below Cylinder |
| Soil Water Content* (%) | 61.3 | 64.9 | 56.4 | 50.4 | 61.4 |
| Soil Undrained Shear Strength* (kPa) | 13.5 | 13.5 | N/A | N/A | 52.5 |
| Iron Oxide $Fe_2O_3$ in Soil (%) | 5.74 | 5.57 | 11.78 | 14.31 | 10.29 |
| Specific Surface ($m^2/g$) | 23 | 23 | 34 | 31 | 33 |
| CEC (meq/100 g soil) | 6.7 | 9.1 | 26.4 | 20.8 | 18 |

Note:

* - Average measured at 5 cm, 15 cm and 45 cm depth at different locations around cylinders.

The adhesion coefficient $\alpha$ of 0.87 is calculated using Eq. 1. This adhesion coefficient for the consolidated Yulchon clay is in good agreement with values suggested in literature for the similar undreained shear strength (CFEM, 1992).

X-ray fluorescence (XRF), specific surface and cation exchange capacity (CEC) analyses were performed on the soil samples to detect the chemical changes in the soil due to electrokinetic treatment. The XRF analyses provide the major element composition of the soil. The results of the analyses show that the percentage of iron oxide ($Fe_2O_3$) increased significantly in the soil after electrokinetic treatment, while the percentages of other oxides (e.g., $SiO_2$, $TiO_2$, $Al_2O_3$, MnO, MgO, CaO, $K_2O$, $Na_2O$, $P_2O_5$, $Cr_2O_3$) only slightly changed. As shown in Table 2, the percentage of iron oxide, an amorphous compound known as a natural cementing agent, increased from 5.7 % to 14.3 %, indicating the increase in the percentage of iron oxide in the cemented soil between the wall of the cylinder and electrodes of 2.5 times. Significant increase in the iron oxide content is also evident in the soil at the bottom of the cylinder and between the electrodes. The increase in iron oxides is also confirmed by the change in the soil colour from grey to yellowish-brown in the zone of effectiveness. The source of the iron was from the steel electrodes, which corroded during the electrokinetic treatment. The released iron precipitated as oxide or hydroxide due to the extremely low solubility of iron in the normal pH range of soils. The iron oxide absorbed on soil particle surfaces induced a cementation effect that led to the consequent development of strong aggregation of soil particles and thus an increase in the soil shear strength and pullout capacity. The electrodes and cylinders were inspected thoroughly after their extraction and it was found that the electrodes corroded extensively. The cylinder changed colour but attempts to measure the thickness of the cylinder showed that there was no change.

The results of specific surface and CEC analyses of the treated soil are listed in Table 2. For comparison, the corresponding values of untreated soil are also included in the table. From the table it can be seen that the values of specific surface and CEC of the electrokinetically treated soil particles were higher than those of untreated soil. This increase in specific surface area, and thus in the CEC, confirms the presence of the higher content of iron oxides in the treated soil because it is know that iron oxides have high specific surface area as coatings on other particles (Dixon et al., 1977).

Scanning electron microscopy analyses were undertaken in order to identify the occurrence of cementation in the soil due to electrokinetic treatment. Figures 8 (a) and (b) show electron microscopy images of the untreated (control) and treated soils, respectively. From figures it is evident that some amorphous cementation compound(s) were formed due to the treatment and filled the interparticle space. These probably include goethite ($\alpha$-FeOOH), ferrihydrite ($Fe_5HO_8 \cdot 4H_2O$) and/or maghematite ($\gamma$-$Fe_2O_3$) (Dixon et al., 1977). These newly formed compounds may explain the cementation of soil particles and increase in bonding between the soil and metal objects and the soil particles by themselves.

## 6 CONCLUSIONS

An experimental program in a large scale laboratory testing facility was performed to develop an in-situ practical design methodology of using electrokinetics for increasing the load-carrying capacities of offshore foundations embedded in soft marine deposits. From the results the following conclusions may be drawn:

1. The pullout capacity of a cylindrical steel foundation model increased five times (~400 %) due to electrokinetic treatment.
2. The electrokinetic treatment can accelerate not only the post-failure recovery for the pullout resistance, but also induce a similar increase of capacity of approximately 400 %.
3. The electrokinetic treatment induced a change in failure mechanism from slippage at the steel/soil interference to failure in the soil mass involving a large volume of soil.
4. The improvement in pullout resistance is attributed to electro-cementation of soil particles and bonding between soil solids and the steel objects by iron oxides.
5. The electrode configuration and the applied voltage of 5.2 V were adequate to create the electric field intensity of between 25 V/m and 200 V/m around the cylinder to initiate the electro-cementation processes in the surrounding soil.
6. Corrosion of steel electrodes due to electrokinetic treatment is responsible for the formation of iron oxides in the soil, which serve as a cementing agent for soil particles during the electro-cementation processes.

## ACKNOWLEDGEMENT

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## REFERENCES

ASTM 1995. Standard method for field measurement of soil resistivity using the Wenner-four electrode method. *ASTM*, G57-95a, 211-215.

CFEM 1992. Canadian foundation engineering manual. *Canadian Geotechnical Society*, 3rd Edition.

Dixon, J.B., Weed, S.B., Kittrick, J.A., Milford, M.H., and While, J.L. 1977. Minerals in soil environments. *Soil Science Society of America,* 145-176.

Lo, K.Y., Micic, S., Shang, J.Q., Lee, N.Y., and Lee, S.W. 2000. Electrical strengthening of a marine sediment. *International Journal of Offshore and Polar Engineering*, 10(2), 137-144.

Micic, S., Shang, J.Q. and Lo, K.Y. 2003. Improvement of the load-carrying capacity of offshore skirted foundations by electrokinetics. *Canadian Geotechnical Journal*, 40, 949-963.
Milligan, V. 1994. First application of electro-osmosis to improve friction capacity-three decades later. *Proceedings of the 13$^{th}$ International Conference on Soil Mechanics and Foundation Engineering*, 5, 1-5.
Prakash, S. and Sharma, H. 1990. Pile foundation in engineering practice. *John Wiley and Sons, Inc., New York*.
Russell, W.B., Saville, D.A. and Schowalter, W.R. 1989. Colloidal dispersions. *Cambridge University Press, Cambridge*.
Soderman, L.G. and Milligan, L. 1961. Capacity of friction piles in varved clay increased by electro-osmosis. *Proceedings of the 5$^{th}$ International Conference on Soil Mechanics and Foundation Engineering*, 2, 143-147.