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Research Article

Performance Improvement in Pile Anchor System for Deep Foundation Excavation Using Electroosmotic Chemical Treatment

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Anchoring force is vital to ensure the acceptable performance of a pile anchor system when supporting deep foundation excavation. The soft soil has several physical properties, such as low shear strength, high water content, large void ratio, and high flowability. Traditional grouting and anchoring techniques have demonstrated technical limits to deal with these soil properties in engineering projects, and accordingly, the anchoring force in the pile anchor system is difficult to meet design requirements. This paper conducted an experimental investigation on the performance improvement in a pile anchor system using the electroosmotic chemical treatment method, with an emphasis on the deep foundation application. Experimental tests and field studies were designed to enhance anchor capacity of a pile anchor system using self-designed devices. The laboratory experiments utilized a simplified anchor system in which anchors were designed as the electrodes to conduct the electroosmotic chemical treatment and consolidate the soft marine soil collected from the project site. In addition, static load tests were conducted on the tested soil to measure the anchoring force. Finally, parametric analyses were performed to investigate effects of several parameters on anchoring force in terms of the ultimate pull-out capacity of the anchor, identifying critical parameters for the field study. Based on laboratory test results, field studies were carried out in the Yingkou city. The results from field studies were compared with laboratory test results to validate feasibility of electroosmotic chemical treatment for a pile anchor system.

1. Introduction

Numerous research studies have been conducted that investigated feasibility of the electroosmotic technique for soft soil using experimental tests and filed studies since the technique was proposed by Reuss in 1809 [1]. Electroosmotic chemical treatment (ECT) is developed by injecting salt solution during electroosmosis to improve the mechanical strength of the soils based on the electroosmotic technique. The salt solution is injected into the soil during electroosmosis, resulting in the improvement in the traditional electroosmosis technique. This technique is performed to (i) reduce electrode erosion, (ii) increase soil electroconductivity, (iii) enhance the speed of draining water during electroosmosis, and (iv) promote aggregation of soil particles due to ionic exchange. Therefore, a substantial increase in the soil strength is obtained to increase consolidation efficiency for soft soil [2, 3]. Chien studied the application of ECT on the foundation [4]. Ou et al. completed an experimental investigation on sedimentary soil using self-designed experimental devices and discussed effects of type and concentration of the salt solution on the soil consolidation, verifying the feasibility of ECT for the soft soil [5]. Chang et al. investigated the effect of calcium chloride solution with various concentrations on the consolidation improvement for soft soil under various

charging conditions [6]. The results identified that the bearing capacity of consolidated soil was enhanced as the aggregation of soil particles occurred in experimental tests [7].

A pile anchor system is a complex structural system installed in soil to protect and retain foundation excavation. Difficulty in theoretical investigations and practical applications for engineering projects has been shown because of the complexity of this system and large foundation deformation. A prestressed anchor is designed as a flexible component to resist tension force in the pile anchor system. As ECT is utilized in the pile anchor system, these prestressed anchors are replaced by normal electrodes to transfer electricity inside the soil. The soils in the vicinity of these anchors are consolidated by the colloids generated from electrode erosion to increase the anchoring force.

Many researchers have reported the effectiveness of the ECT technique to consolidate the soft soil foundation, but limited studies have evaluated its feasibility to improve the performance of the pile anchor system for deep foundation excavation. According to the engineering projects, this paper conducted an experimental investigation on the performance improvement in an anchor pile system using ECT for deep foundation excavation. A laboratory experiment was performed to consolidate soft soils considering various parameters, i.e., potential gradient and salt solution, using self-designed devices. Furthermore, the pull-out capacity of the anchor was evaluated using the static load test. Finally, a field study was carried out in Yingkou to validate the laboratory experimental results and determine the feasibility of ECT on the improvement in anchoring force.

2. Laboratory Tests of ECT

The experimental test was carried out on soils collected from a marine clay deposit in a coastal industrial base of the Yingkou city. The soil samples with grey-black colour which were shown to have low bearing capacities were obtained at a depth of 13 m under the ground and then transported to the laboratory. The collected soils were dewatered, triturated, levigated, sieved, and remodelled with deionized water. The water content of the remodelled soil was set to 50%. The physical and mechanical properties of the untreated soils are listed in Table 1.

2.1. Experimental Cell. The laboratory tests of ECT were performed using a soil tank with dimensions of 300 mm × 200 mm × 250 mm, which was made of engineered plastics. A steel bar with a diameter of 8 mm and a length of 250 mm was inserted into the soil up to a depth of 200 mm and used as the anode in electroosmotic chemical treatment. The cathode made from a steel pipe with a diameter of 12 mm and a length of 250 mm was inserted into the soil up to a depth of 200 mm. In order to inject salt solution, a 15 mm diameter PVC pipe was bundled with an anode. Some holes were drilled evenly around the pipe wall, allowing the salt solution to move freely from the PVC pipe into the soil. In the traditional method, the salt solution was added in the steel pipe, and the steel pipe was ruptured quickly. A PVC pipe is a useful device to prevent the anode from eroding.

The schematic configuration of ECT is shown in Figure 1. The apparatuses consisted of a regulated power supply (0~30 A, 0~100 V), a soil tank, electrodes, an ammeter, a voltmeter, and auxiliary apparatuses (including multimeters, thermometers, soil conductivity meters, and pocket penetrometers). The electrodes were connected to a regulated power supply to provide direct current for soil under normal temperature and humidity. The laboratory tests were modelling a normal environment in field studies. During the testing process, the soil was dried under a designed natural temperature, and geotextile fabrics were placed at left and right sides of the soil tank. The ammeter and the voltmeter were utilized to record the current and voltage of the soil during testing. A graduated cylinder was used to collect and measure the water drained from the soil using the ECT technique. The dewatering amount was recorded and calculated during testing.

2.2. Test Methods. Three laboratory tests were designed and conducted in this study. The test conditions and basic parameters are listed in Table 2. The cement paste with a water-cement ratio of 3 : 1 was added in the tests. Research identified that the cement paste is not a high-performance material for ECT [8, 9], but the cement paste is commonly used as a grouting material in engineering projects. As such, the cement paste was employed as the grouting material for the current study. The electrodes were connected to the power supply with the variation of the potential gradients. During the testing process, the cement paste was added from the anode to the soil at a certain time interval. The volume of the injected cement paste was 5 mL each time. The tests were finished when the recorded current decreased to 0 A. After the electroosmotic chemical treatment test was completed, a series of chemical reactions would be processing in the tested soil samples because of electroosmosis and chemical grouting, with ionic exchange and precipitation occurred during the process. As a result, the tested soil samples were placed and cured for 36 hours after the electroosmotic chemical treatment test was completed. Then, the static load test was carried out on the posttested soil to determine the soil capacity.

2.3. Test Results. Figure 2 illustrates the current-time histories for three tests. The currents were shown to have same change trends. The maximum currents in tests I~III were recorded as 0.93 A, 1.09 A, and 1.53 A, respectively. The current in the soil increased rapidly when charging from 0 to 3 hours. This finding was attributed to high water content of the original soil and occurrence of chemical reactions near the electrodes, resulting in high moving speed of ions and increased electrical conductivity. After charging 3 hours, dewatering, ion movement, and precipitation occurred on the soil during the ECT. The contact between electrodes and soil was compromised by several pores generated from the ECT and accordingly reduced the current. It was concluded

Table 1: Physical and mechanical properties of the soil.

Parameters	Unit	Values			
		Average values	Maximum values	Minimum values	Standard values
Water content	%	46.6	53.7	44.2	46.3
Unit weight	kN/m^3	17.5	18.5	16.8	17.5
Porosity ratio	—	1.29	1.64	1.03	1.27
Saturation	%	99.1	100	95.1	99.08
Liquidity index	—	1.64	2.07	1.01	1.69
Plasticity index	—	15.9	16.8	14.6	15.8
Cohesion	kPa	5.7	7.8	3.1	5.4
Friction angle	°	2.6	4.1	1.5	2.43

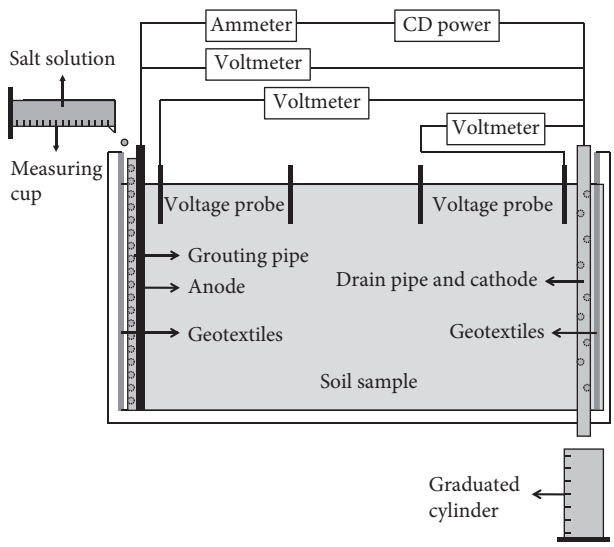

Figure 1: Schematic configuration of electroosmotic chemical treatment.

Table 2: Parameters of laboratory tests.

No.	Potential gradient (V/cm)	Water-cement ratio	Charging time (h)	Curing time (h)
Test I	1.25	3 : 1	23	36
Test II	1.75	3 : 1	23	36
Test III	2.25	3 : 1	23	36

from Figure 2 that an increase in the potential gradient resulted in an increase in the current under the same conditions.

Energy consumption is an accumulated value during the ECT process. The longer charging time leads to more energy consumptions. The energy consumption-time histories for three tests are shown in Figure 3. In tests I~III, the ultimate energy consumptions were 236.9 W·h, 392.3 W·h, and 689.2 W·h, respectively. The energy consumption increased with the increasing potential gradient. The increasing speed of energy consumption in test III was much higher than that in tests I and II. The speed of ion movement and the conductivity improvement of the soil were enhanced by injecting the cement paste into the soil to increase the current. As such, the energy consumption increased as the current increased. Based on Figures 2 and 3, the changing trend of the energy consumption was identical with that of the current.

The dewatering amount-time histories for all tests are shown in Figure 4. The ultimate dewatering amounts in tests I~III were 340 mL, 530 mL, and 543 mL, respectively. The dewatering amount increased with an increase in the potential gradient. The dewatering amount in test II was equal to that received in test III. Based on Figures 3 and 4, the energy consumption in test III was much higher than that in test II, and the dewatering efficiency of test II was superior to that of tests I and III when comparing dewatering amount and energy consumptions.

According to the dewatering amount-time histories, a hyperbola model, as shown in equation (1), was selected to fit the dewatering amount:

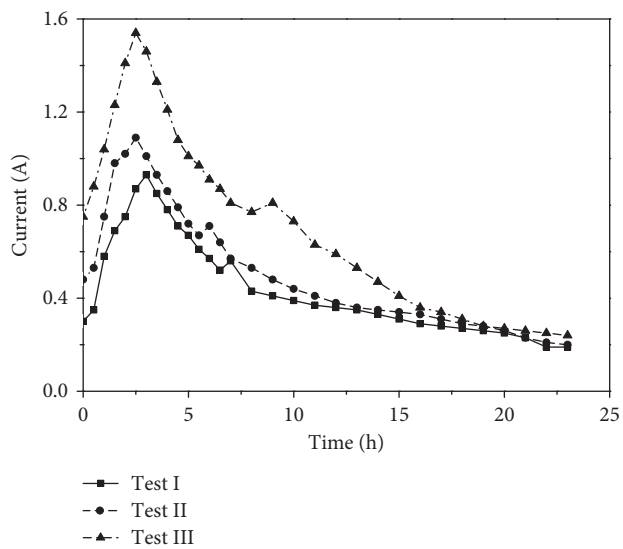

Figure 2: Current-time curves.

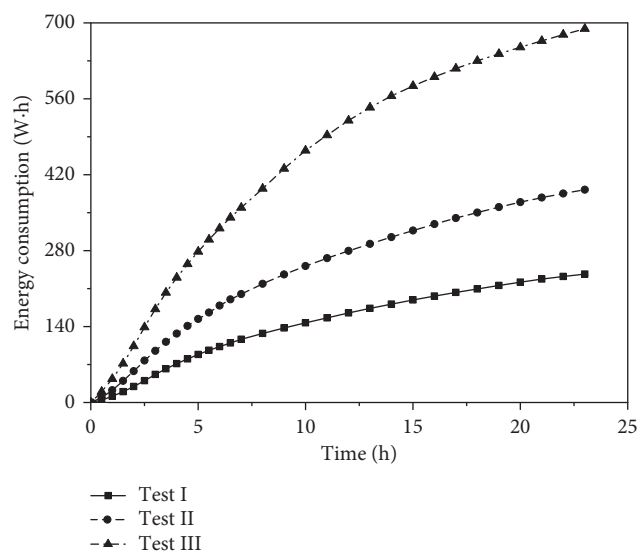

Figure 3: Energy consumption-time curves.

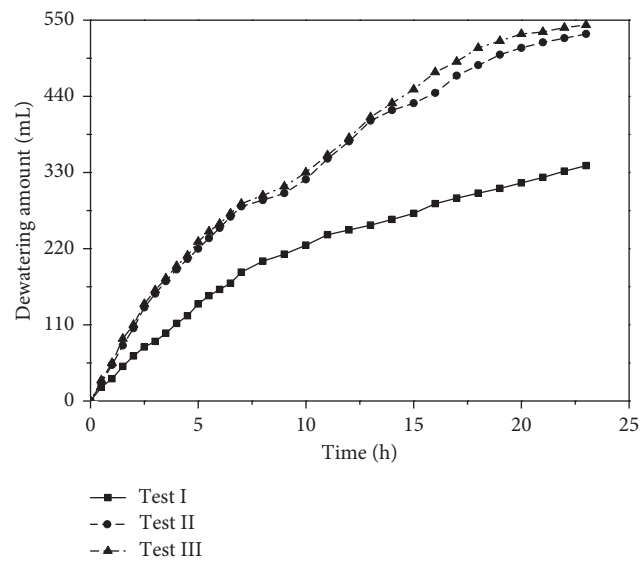

Figure 4: Dewatering amount-time curves.

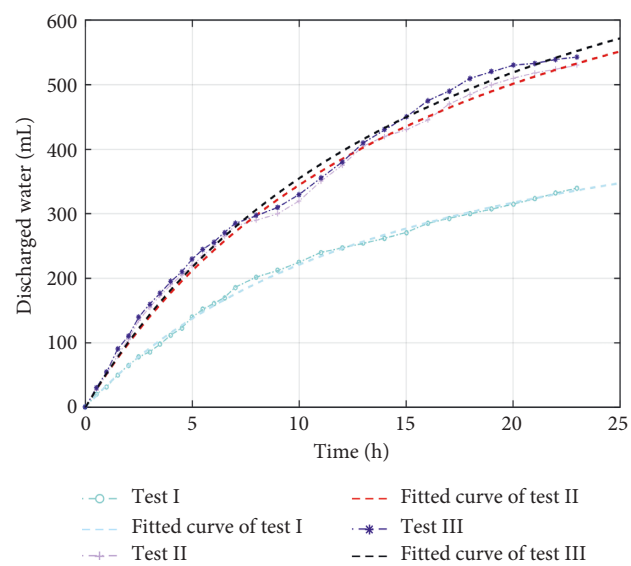

Figure 5: Fitted dewatering amount-time curves.

$$\frac{1}{Q} = a + \frac{b}{t}. \tag{1}$$

Figure 5 shows the fitted dewatering amount-time histories. The coefficients for tests I~III were calculated. The fitted coefficient a ranged from 0.001 to 0.003, and b ranged from 0.015 to 0.04. As shown in Figure 5, the selected hyperbola model was accurate to demonstrate the change trend of the dewatering amount, which can be used to calculate the dewatering amount of soft soil from the ECT method.

According to the theory of electroosmosis proposed by Esrig [1], the amount of dewatering is calculated using

$$Q = v_e t, \tag{2}$$

$$v_e = k_e \frac{\Delta\phi}{L} A, \tag{3}$$

where Q is the total amount of dewatering at a certain time t; v_e is the speed of dewatering; t is the charging time; k_e is the electroosmotic coefficient; $\Delta\phi$ is the effective potential, namely, the potential difference between two ends of the soil; L is the length of the soil which is defined as the distance between the anode and the cathode; and A is the soil cross-sectional area. The speed of dewatering can be determined at a certain time using equations (2) and (3). As shown in Figure 4, the dewatering speed in the first 7 h was higher than that in the last 14 h. It was concluded from Figure 2 that the current in the first 7 h was larger, and the speed of chemical reaction occurred in the soil was higher, with a higher dewatering speed. The dewatering speed in tests II and III was calculated as 0.0111 mL/s for the first 7 h and 0.0083 mL/s for the late 14 h using equation (3).

Based on equations (2) and (3), the electroosmotic coefficient is expressed as

$$k_e = \frac{QL}{\Delta\phi At}. \quad (4)$$

The electroosmotic coefficient of the soil was obtained using equation (4). Figure 6 shows the electroosmotic coefficient curves in tests I~III.

As shown in Figure 6, the electroosmotic coefficients decreased with time during testing. The electroosmotic coefficients were determined from the electroosmosis and suction force of the soil in this study [10]. The electroosmotic coefficient curves in tests I~III were similar to the exponential curve, and the electroosmotic coefficient curves were fitted using the exponential model as

$$y = m - n \cdot k^x, \quad (5)$$

where m, n, and k are the coefficients for the fitted curves, which are related to the mineral composition of the soil, potential gradient, and injected salt solution. The value of m, n, and k ranged from 5 to 7, 12 to 15, and 0.8 to 0.9, respectively.

The dewatering speed curve was determined using the fitted model of dewatering amount and the relation between dewatering amount and dewatering speed as shown in equation (6). The dewatering speed has a significant effect on the electroosmotic coefficients:

$$v = -\frac{b}{t^2}. \quad (6)$$

The formula to calculate the electroosmotic coefficient in terms of time was proposed based on equation (3), which provides more accurate estimation of the electroosmotic coefficient for engineering projects, as follows:

$$k_e = -\frac{bL}{\Delta\varphi At^2}. \quad (7)$$

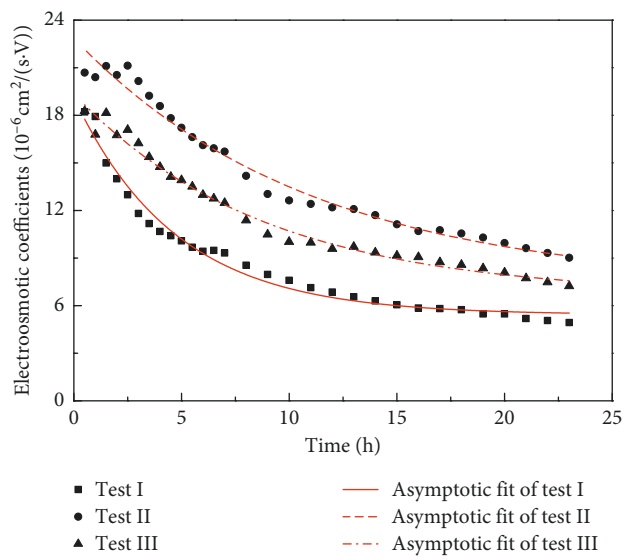

Figure 6: Electroosmotic coefficient-time curves.

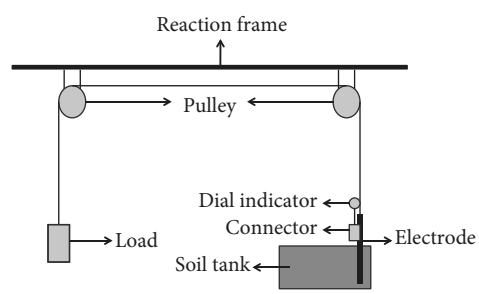

Figure 7: Schematic configuration of the static load test.

3. Static Load Test

3.1. Test Setup. A static load test was conducted using the self-designed pull-out testing devices to measure the anchoring force in the soils. The apparatus in the self-designed devices consisted of reaction frames, pulleys, an electronic scale, a dial indicator, and connectors. The reaction frames fabricated with the angle iron were employed to support the testing devices. The vertical displacement of the test anchor under the applied load was measured using a dial indicator. The schematic configuration of the static load test is shown in Figure 7.

3.2. Test Results. The consolidated soils were cured for a certain time and placed below the reaction frame. The steel strand was connected to the anchor used as the anode in the ECT method. According to the requirements mandated in geotechnical anchoring specification, specifications for bolt-shotcrete support, and codes for design of building foundation [11–13], a static load was applied to the device at an increment of 4.9 N, and the displacement was recorded using the dial indicator at every increment of load. The ultimate pull-out capacity of the anchor was obtained in the static load test. Based on the ultimate pull-out capacity, the effects of experimental parameters on anchoring force were evaluated to examine the appropriate parameter for ultimate pull-out capacity improvement. Figure 8 shows the anchor cable for the anodes in different tests.

The objectives of this research were to determine the feasibility of ECT for the performance improvement in the pile anchor system and to obtain the anchor capacity by measuring the anchoring force. Therefore, the load-bearing capacity in the surface of the soil was measured for this research, and the experimental method was the same as that in the related research studies [8, 9]. The ultimate load-bearing capacities of soils in tests I~III were obtained as 104.4 kPa, 135.2 kPa, and 129.7 kPa, respectively. The static load test was performed on the anchor cable in the anode to determine its pull-out capacity. The results provided the experimental reference values of pull-out capacity for this type of soft soil and suggestions for engineering projects. The static load was applied until one of the following cases occurred according to the rule of M.0.4 in GB50007-2011 [13]: (1) the increase in the load was not stable for 1 hour; (2) there was a slight or no increase in load; and (3) anchor failed or was pulled out from the soil. The ultimate pull-out

(a) (b)

Figure 8: Tested anchor cables for different tests.

capacity is defined as the load at which the test has been stopped.

The load-displacement curves received from the static load test are shown in Figure 9. When the anchor was pulled out from the soil in tests I~III, an inflection point was observed in these curves. According to the requirements provided by CECS 22:2005 [11], the ultimate pull-out capacities of anchors in tests I~III, which were defined as the initial inflection points, were 44.1 N, 93.1 N, and 53.9 N, respectively. The ultimate pull-out capacity of the anchor in test II was larger than those in tests I and III. The ultimate pull-out capacities of anchors were improved for all three tests. A large amount of Na^+ and $SiO_4{}^{2-}$ were added because of the injection of cement paste, resulting in the increase of ion movement and the enhancement of chemical reactions to generate the colloid. The soil strength was improved because of the generation of colloids. Furthermore, the strength of the cement paste provided contributions to the increase in soil strength. The ultimate pull-out capacity in test III was much less than that in test II. The erosion rate of the anode in tests I~III was 14.52%, 10.94%, and 28.13%, respectively. The largest anode erosion occurred in test III. It was concluded that the 1.75 V/cm potential gradient provided the best consolidation effect with the largest ultimate pull-out capacity of the anchor.

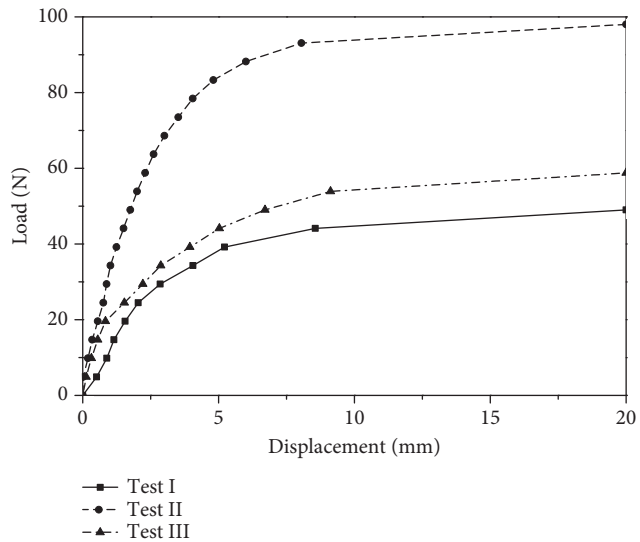

Figure 9: Load-displacement curves of the static load test.

4. Field Study

4.1. Project Description. According to the "Geotechnical Investigation Report of Wanda Plaza in Yingkou City" provided by the Survey Research Institute of Liaoning GEO-Engineering Group Corporation, the site soil is made up of twelve layers from the surface. The physical and mechanical properties of each layer of the soil which were determined using direct shear are listed in Table 3. Because of the low content of silt particles in the tested silty clay, the friction angle of the silty clay in the report was smaller than usual. And the values of the friction angle were confirmed with the staff who completed the report in the Survey Research Institute of Liaoning GEO-Engineering Group Corporation.

The test was performed at a depth of 13 m under the ground to enhance the capacity of the anchor for deep foundation excavation. The soil texture at this depth was composed of marine clayey soil. The marine clayey soils with grey-black colour were presented in the field, including some sand soils with a thickness of 0.2~0.3 m. The saturated clayey soil with a small bearing capacity had a high compressibility. The traditional anchoring technique was not applicable for engineering requirements. The ECT technique was proposed to consolidate the soft soil in the field study.

4.2. Test Method. A high-strength, low-relaxation, unbonded steel strand was utilized to fabricate the anchor cable. The normal Portland cement with the strength larger than 42.5 MPa was used as the cement paste. The mix proportion for the cement paste was 1 : 0.5 : 0.01 : 0.1 of cement : water : water reducer : expanding agent. The pressure grouting method was employed to grout the cement paste into the anchor. The early strength agent was used for the cement in this field study. The diameter of the jet grouting volume was not less than 300 mm. Table 4 lists the test parameters for various anchors.

Four adjacent anchor cables were used in the test. Three anchors were selected discretionarily to perform the ECT technique, and the remaining one was treated as a control

Table 3: Physical and mechanical properties of each layer of soil.

No.	H (m)	N	C_u (kPa)	Φ (°)	γ (kN/m^3)	K (m/d)
1	0.50~4.50	Miscellaneous filler	0	0	16.6	0.5
2	0.50~3.80	Silty clay	6.5	2.4	19.2	0.1
3	2.30~7.40	Interbedded silty clay and sand	12.0	6.5	18.7	0.5
4	9.30~14.0	Sand	0	23	18.5	1.0
5	12.60~16.30	Marine clay	6.8	3.5	19.4	0.1
6	13.50~18.00	Sand (slightly dense)	0	24	18.5	1.5

Note: H is the thickness of each soil layer; N is the soil texture of each layer; C_u is the cohesive force of the soil; φ is the friction angle of the soil; γ is the unit weight of the soil; K is the hydraulic conductivity.

Table 4: Test parameters of the anchors.

Specimen	Soil layer	Cement	Anchoring length (m)	Model	Ultimate capacity (kN)
SA-I	Marine clay	M42.5	18	$4 * 7\Phi5$	320
SA-II	Marine clay	M42.5	18	$4 * 7\Phi5$	320
SC-I	Marine clay	M42.5	18	$4 * 7\Phi5$	320
WS-I	Marine clay	M42.5	18	$4 * 7\Phi5$	320

test. In these selected anchors, the middle one (marked as SC-I) served as the cathode, and the other two anchors (marked as SA-I and SA-II) were set as the anodes for the ECT. The remaining anchor (marked as WS-I) was not consolidated in order to compare the results with those of the consolidated anchor. When subjected to electronic potential, the soil particles were aggregated to the anode, and the water flowed to the cathode during electroosmosis. The oxidation reactions occurred in the cathode to generate the Fe^{2+} and Fe^{3+} soil colloids. The soil particles were cemented because of these soil colloids, causing the development of anchorage volume in the vicinity of the anode. The schematic of the field study using ECT is shown in Figure 10.

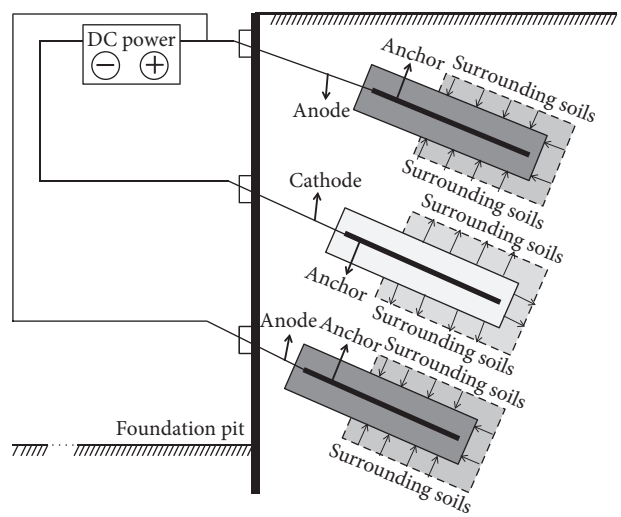

Figure 10: Schematic of the field study using ECT.

4.3. Test Results. An adjustable power supply (0~150 A, 0~100 V) was used to provide the potential for the soil. An isolation transformer was placed to ensure electrical safety. The distance of the adjacent anchor cable was 2 m. The potential gradient was set to 25 V/m. The initial, ultimate, and average currents were 150 A, 97.6 A, and 121.1 A, respectively. Figure 11 illustrates current-time history obtained from the field study. As shown in the figure, the current decreased with an increase in charging time. This finding was attributed to the following reasons: (1) Oxidation reactions and erosion occurred in the anodes. A large number of free ions were added with the cement paste, and chemical reactions were developed in the soil to considerably reduce the water content. (2) The soils in the vicinity of the electrodes were loosened to weaken the soil conductivity. The decrease in the conductivity led to the decreasing current. (3) The soil conductivity was reduced because of the appearance of cracks. The current-time curve was fitted using a linear regression as shown in Figure 11.

After the field study was completed, a pull-out test was performed on SA-1, SA-2, and WS-I to examine the anchoring forces. According to the requirements in CECS 22: 2005 [11], GB 50086-2015 [12], and JGJ 120-2012 [14], the maximum test load was selected as 1.5 times the design tensile strength for the permanent anchor. The pretension

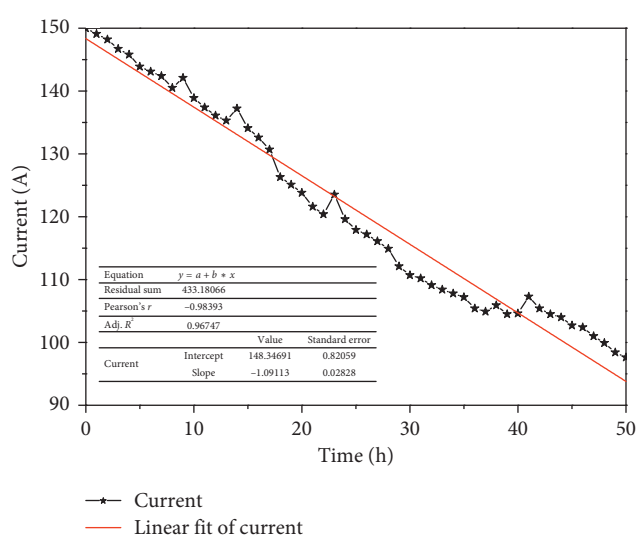

Figure 11: Current-time curve and fitted curve in the field study.

was conducted on the anchors, and the tension was selected as 0.1 times the design tensile strength of the anchor to delete the inelastic deformation of the anchor. Then, the initial load was applied as 0.3 times the anchor design tensile strength. Finally, a pull-out load was applied at a certain increment for anchors, and the load was selected as 0.50~1.50 times the design tensile strength. In the static load test, the load at each increment should be lasted for a certain time. If the displacement increments in the first 10 min were larger than 1.0 mm, the load should be lasted for 50 min. The pull-out load increased to 1.05 times the design tensile strength. According to design axial tension capacity and the CECS 22: 2005 requirements, the critical loads were obtained.

The maximum test load was

$$P_{\max} = 1.50N_t = 1.50 \times 320 = 480\,\text{kN}. \quad (8)$$

The locked load was

$$P = 1.05N_t = 1.05 \times 320 = 336\,\text{kN}. \quad (9)$$

The initial load was

$$P_0 = 0.10N_t = 0.10 \times 320 = 32\,\text{kN}. \quad (10)$$

The qualification of the pile anchor system should satisfy requirements provided in CECS 22:2005 and GB 50086-2015: (1) The total displacement corresponding to the maximum test load should be larger than 80% of the elastic elongation of the anchor under the maximum load and less than the sum of unanchored length of the anchor and 1/2 anchored length. (2) The creep deformation of the anchor at the last load increment should not be larger than 1.0 mm within 1~10 min. If the creep deformation is larger than 1.0 mm, the creep deformation should not be larger than 2.0 mm within 6~60 min.

The load-displacement curves of the anchors WS-I, SA-I, and SA-II are shown in Figures 12~14, respectively. As shown in Figure 12, the accumulated displacement of WS-I increased to 5 times the displacement at the previous level when the load increased to the fifth level. The ultimate pull-out capacity of the WS-I anchor was 240 kN, which was less than the design pull-out capacity of 320 kN. The anchoring force did not meet the requirements. This finding was due to several reasons: (1) High water content of the soil was caused by the abundant underground water in this field. The adequate anchoring force was not generated owing to the low bearing capacity of the soil surrounding the anchor. (2) The curing time for the concrete was shorter than the designed period, resulting in an insufficiency in the pretension time for the anchors. The anchor did not reach its design anchoring force in a short time to meet the code requirements.

As shown in Figures 13 and 14, the maximum accumulated displacement of SA-I was 16.44 mm, with a 6.16 mm residual displacement. The rebound rate was determined as 62.53%. For SA-II, the maximum accumulated displacement was 17.31 mm, with a residual displacement of 5.94 mm. The rebound rate was determined as 65.68%. The elongation based on anchor tension theory in CECS 22:2005 was expressed as

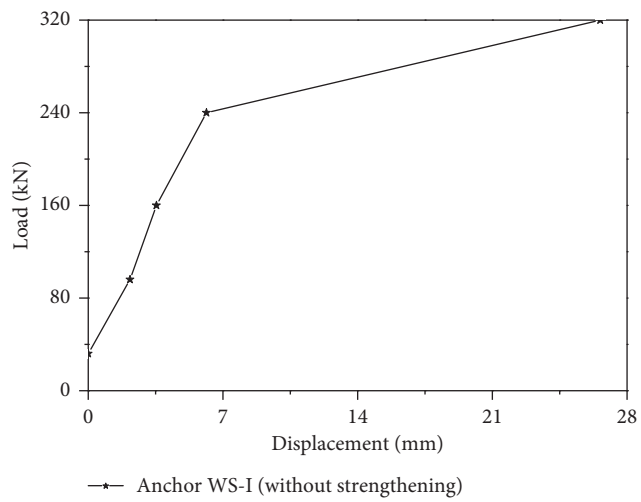

Figure 12: Load-displacement curve of the anchor WS-I.

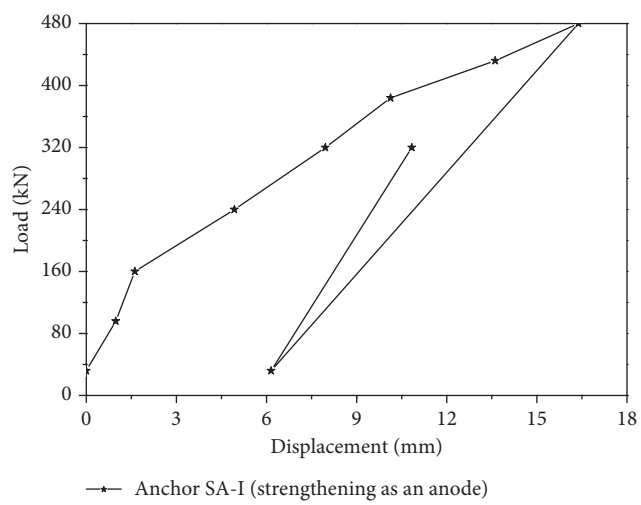

Figure 13: Load-displacement curve of the anchor SA-I.

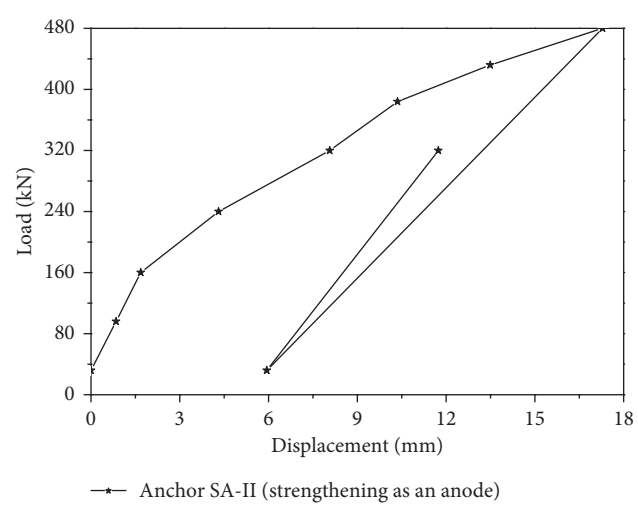

Figure 14: Load-displacement curve of the anchor SA-II.

$$\Delta L = \frac{N_t L}{EA}, \tag{11}$$

where ΔL is the elongation based on anchor tension theory, N_t is the tension in the anchor, E is the elastic modulus of the steel strand, L is the anchor tensioned length, and A is the cross-sectional area.

According to GBT 5224-2014 [15], the cross-sectional area and elastic modulus of the anchor were $A = 139\,\text{mm}^2$ and $E = 1.95 \times 105\,\text{MPa}$, respectively. The test load of SA-I and SA-II was selected as 480 kN. The total length of the anchor was 18 m, the anchored length of the anchor (L_{mg}) was 8 m, and the unanchored length of the anchor (L_{zy}) was 10 m. The critical parameters of SA-I and SA-I can be obtained using equation (11).

(1) The elongation of the unanchored part of the anchor is

$$\begin{aligned} \Delta L_1 &= \frac{1.50 N_t L_{zy}}{EA} = 17.71\,\text{mm}, \\ 0.8\Delta L_1 &= 0.8 \times 17.71 = 14.17\,\text{mm}. \end{aligned} \tag{12}$$

(2) Theoretical elongation obtained according to the sum of the unanchored length of the anchor and 1/2 of the anchored length is

$$\begin{aligned} L' &= L_{xy} + 0.5 L_{mg} = 14\,\text{m}, \\ \Delta L_2 &= \frac{1.50 N_t L'}{EA} = 24.97\,\text{mm}. \end{aligned} \tag{13}$$

The elongations for SA-I and SA-II corresponding to $1.50N_t$ in the test were 16.44 mm and 17.31 mm, respectively. The displacements at anchor heads were larger than 80% of the theoretical elongation of the unanchored length and less than theoretical elongation obtained according to the sum of the unanchored length of the anchor and 1/2 of the anchored length. It was concluded that SA-I and SA-II satisfied the requirements for the project. A creep test was conducted on SA-I and SA-II with the loads of 0.25, 0.50, 0.75, 1.0, 1.20, and $1.50N_t$. The recorded time at each load level was 10, 30, 60, 120, 240, and 360 min. The creep amount was recorded at a certain time interval in 360 min at each loading level. Based on the creep test results, the ultimate creep amounts for SA-I and SA-II were less than 2 mm, which satisfied the requirements.

5. Conclusions

This study conducted a laboratory experimental investigation on the performance improvement in a pile anchor system for deep foundation excavation using the ECT technique. Laboratory tests were carried out to consolidate marine soft soils collected from Yingkou. Static load tests were performed to determine anchor pull-out capacity in the consolidated soils. Based on the experimental results, field studies were conducted to validate the laboratory experimental results. The following conclusions were summarized in this study:

(1) The potential gradient affected the ultimate bearing capacity and the pull-out capacity of the anchor cable utilized as the anode in the ECT technique. The potential gradient of 1.75 V/cm provided the largest bearing capacity of the consolidated soil and the maximum pull-out capacity of the anchor cable.

(2) The dewatering amount was fitted to obtain an acceptable representation model of the dewatering water-time curve. The dewatering speed curve was determined based on the relation between dewatering amount and speed, which was useful to demonstrate the dewatering efficiency. An empirical formula was developed to identify the relation between dewatering speed and electroosmotic coefficients, providing an accurate estimation for the change trend of electroosmotic coefficients.

(3) The field studies showed that the ultimate pull-out capacities of SA-I and SA-II were improved to meet the design requirements, and the ultimate pull-out capacity of WS-I did not satisfy the design requirements. The field studies demonstrated that ECT is a feasible and useful method to improve anchor pull-out capacity in a pile anchor system for deep foundation excavation.

Data Availability

The experimental data used to support the findings of this study are included within the article. The readers can find the data in the figures or tables presented in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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