

# Electrokinetic Stabilization of Marine Clayey Soils by Different Injection Procedures

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The nonuniform improvement of strength in marine clayey soils is one of a primary problem observed when electroosmosis treatment is conducted in these soils. Five group tests were conducted to access the effect of electrokinetic stabilization on treatment of soft clay by different injection procedure of  $\text{Ca}^{2+}$  and  $\text{SiO}_3^{2-}$  ions. The current, drainage rate, energy consumption and bearing capacity were analyzed. The results show that the injection of  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  at the anode and cathode, respectively, is the most effective operation procedure. Consequently, most of the soil surface bearing capacity is higher than 180kpa, accounting for 70.4% of the total soil sample area, the increase in strength was attributed to injection of up to 43% of chemical additives after a 14-day curing were measured in the middle zone.

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**Keywords:** Electrokinetic Stabilization; Soil improvement; Injection procedure; Chemical solution.

## 1. INTRODUCTION

The worse engineering properties of marine clayey soils often cause problems such as collapsing of foundation pits, uneven settlement, and inclination of structures present on the soil. An economical and effective method must be found to improve the engineering properties of marine clayey soils. Electroosmosis (EO) was first applied in the 1930s to soft clay that possess high water contents, low hydraulic conductivity and low shear strength [1]. This technique applies direct current (DC) through a soil mass using two electrodes. Since then, numerous laboratory experiments have investigated the characteristics of electroosmotic treatment [2-8]. Moreover, several studies have adopted the technique to improve the engineering characteristics of soil, such as improving stabilization slopes, excavations, and embankments[9]; increasing pile capacity[10]; increasing the strength of clays[11-13]; and the treatment of dispersive soils[14, 15].

Several factors have been considered for the less acceptance of EO for common applications, including severe corrosion of electrodes, high energy consumption and the improvement of soil strength within a limited area. Therefore, various methods have been proposed to improve its efficiency, such as intermittent current, electrode reversal, EKG electrodes[16, 17], and a combination of surcharge and vacuum preloading[18] and electroosmotic chemical treatment(ECT)[19]

Based on the EO process, the stabilizing agents are transported into the soil from the electrodes under the applied potential. This technique is called “electrokinetic stabilization”[20], and is more advantageous when the hydraulic conductivity of the soil is low, such as silty and clayey soils[21]. Many studies have adopted this technique and demonstrated its feasibility, availability, and economic efficiency[19, 22, 23]. Cation exchange, cementation, and precipitation can substantially improve strength [24]. Compared with the traditional soil grouting method, electrokinetic stabilization is also suitable when the hydraulic conductivities are less than  $10^{-5}$  m/s, and it has the advantage of undisturbed soil compared with the mix-in-place chemical stabilization.

Gray [25] focused on the electrochemical hardening of different soil types by the electroosmotic injection of aluminum. Their result show that the strength of these soils significantly increased, whereas the liquid limit changed. It was found that the electrochemical induration is critical mechanism contributing to the strength increase in soil. Ozkan [20] injected two types of ions (Al and  $\text{PO}_4^{3-}$ ) during the electrokinetic process, an average shear strength increase of 500%-600% and Atterberg limit increase of 30% were achieved. The results demonstrate that ion exchange and precipitation are the principle attributes to improve kaolinite strength. Alshawabkeh [26] introduced nitric acid amendment into the electrokinetic stabilization specimen for two weeks under controlled pH conditions. The results show that the shear strength increases 160% more than that of the baseline soil.

Many researchers have reported the feasibility and effectiveness of the electrokinetic stabilization technique. However, most of the test set-ups in the literature mentioned above usually consisted of three components, namely that the two electrode compartments are located at the two ends of the soil specimen container and the electrodes were inserted into chemical solutions. Such conditions prevent the electrodes from contacting the soil specimen directly (no existing physical soil–electrode contact) and provide a consistent supply of chemical solution during the tests. This construction is quite different from the field application, as described in the literature.[11, 27]. In addition to the above deficiencies, the investigation of marine clay in Yingkou area using electrokinetic stabilization technique and the effect of operating procedures has not been reported in literature. Given this, this paper describes a series of ECT tests with three pairs of electrodes, vertically inserted into soil specimens with tubular steel electrodes rather than plate or mesh. This study investigates how the operational procedure (types of chemical solution and injected positions) affect the electrokinetic stabilization process in marine clay.

## 2. LABORATORY EXPERIMENT

### 2.1. Materials

The soil used in this investigation was obtained from Yingkou located in the south part of Liaoning Province. The marine clayey samples appeared gray-black and possessed low permeability

bearing capacities. Table 1 shows the basic geotechnical properties of the soil. The soil was first dried and mixed with a proper amount of deionized water. The water content was approximately 47%, and the initial bearing capacity of the remolded sample was 20 kPa.

**Table 1.** Summary of soil properties

	Water Content (%)	Compressibility Modulus (MPa)	Porosity Ratio	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Sensitivity
Soil	46.4	0.48	1.36	32.2	11.1	21.1	90

**Table 2.** Summary of test conditions

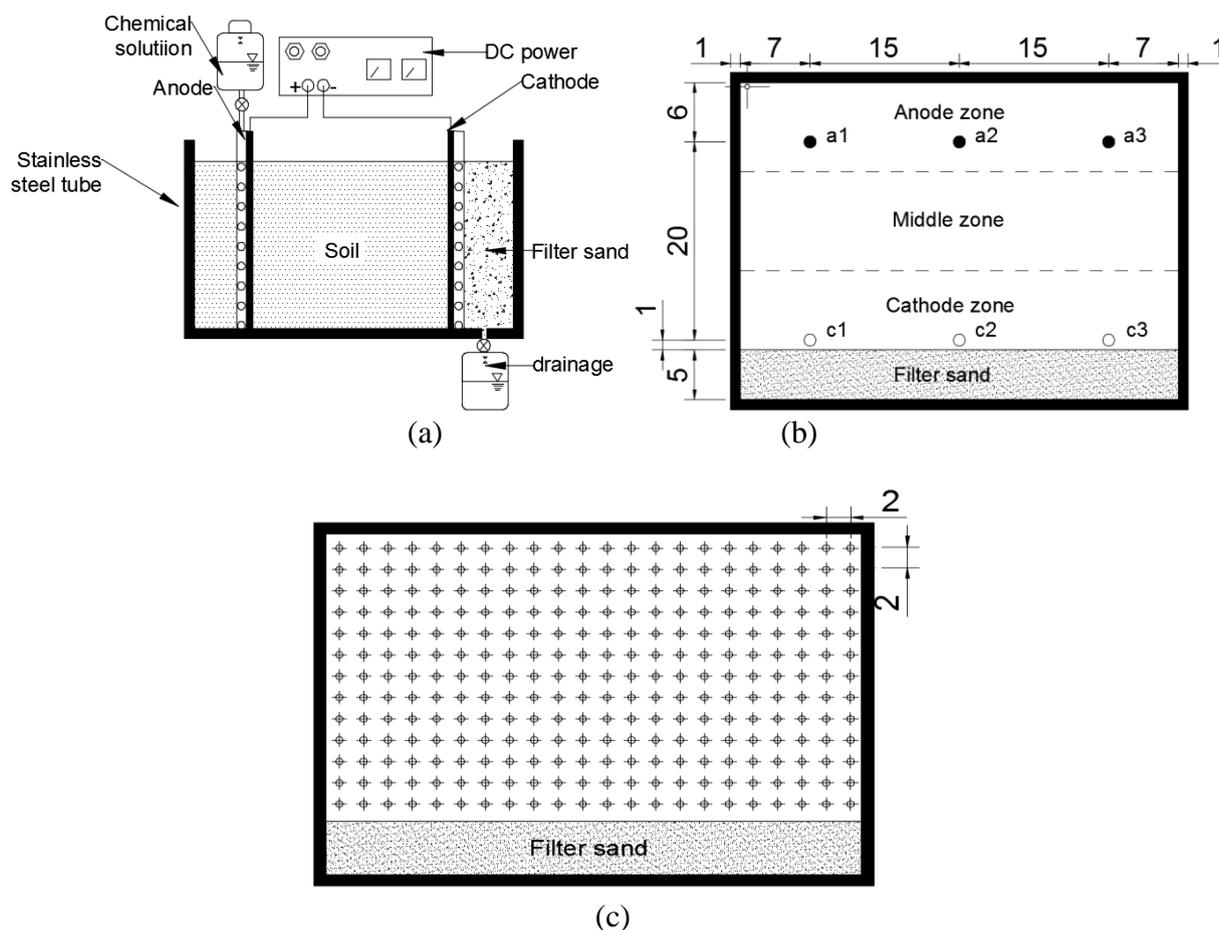
Test No.	Aded Solutions		Total Amount of Solution (mL)	Water Content (%)	Voltage (V)	Total Drainage (ml)	Test Duration (h)
	anode	cathode					
T1	No	No	No	47.06	30	689	16
T2	CaCl <sub>2</sub>	No	120	47.06	30	463	22
T3	NO	Na <sub>2</sub> SiO <sub>3</sub>	120	47.06	30	596	27.5
T4	CaCl <sub>2</sub> Na <sub>2</sub> SiO <sub>3</sub>	No	60 CaCl <sub>2</sub> 60 Na <sub>2</sub> SiO <sub>3</sub>	48.91	30	660	21
T5	CaCl <sub>2</sub>	Na <sub>2</sub> SiO <sub>3</sub>	120 CaCl <sub>2</sub> 120 Na <sub>2</sub> SiO <sub>3</sub>	47.83	30	641	21

## 2.2 Experimental equipment and methods

Figure 1 (a) shows the electrokinetic testing cell based on that described by Zhang et al [28]. The test container was manufactured from 1cm thick acrylic, the rectangular tank was 32 cm long × 42 cm wide × 20 cm deep. Geotextiles were arranged on the two sides of the container to prevent soil particles escaping with the fluid flow. The test cell comprised two compartments, that was filled with soil sample and filter sand, respectively. Six electrodes, as shown in Fig. 1(b), were pushed into the soil in the test cell at a depth of 170 mm. (anodes: a1, a2 and a3; cathodes: c1, c2, and c3). The distances between similar electrodes were 15 cm and 20 cm for opposite electrodes. The steel pipes were 6 mm in diameter and 200 mm long. A PVC pipe with a diameter of 12 mm was bundled with the anode for injecting chemical solution. The tube was covered with geotextile to reduce the loss of soil particles. The diameter of the holes was 2 mm, and the interval between them was 1 cm.

Five electrokinetic tests were conducted, including a pure electroosmosis (EO) and four electro-osmotic chemical treatment (ECT). A constant electrical potential of 30 V was applied to the soil, according to a potential gradient of 1.5 v/cm. A DC power with a maximum capacity of 30 A and 100 V was used. The concentration of CaCl<sub>2</sub> was selected for 1.86 mol/L, as suggested by Zhang [28], and

Na<sub>2</sub>SiO<sub>3</sub> was prepared with the same mass ratio as CaCl<sub>2</sub>, the value was 2.09mol/L. In addition to the EO test, the saline solution of each test was injected into the soil samples by the PVC pipe at 3, 6, 9, and 12 h. T1 was the baseline for the rest of the experiments. The tests duration time ranged from 16 to 23 h. During the treatment period, the electric potential, current and energy consumption were monitored. The drainage was collected every 3 h from cathode. Soil bearing capacity was measured by using a penetrator after the treatment. According to the arrangement of electrodes in the experiment, the measurement places of soil can be divided into the anode, middle, and cathode zones, as can be seen from Fig.1(b), and the specific measurement locations are shown in Fig 1(c).



**Figure 1.** Schematic of the experimental apparatus: (a) Profile, (b) Plan view (c) Measuring points of bearing capacity

### 3. RESULTS ANF DISCUSSION

#### 3.1 Current

Fig 2 presents the development of the current profiles across the specimen during the experiments. The figure shows that the changes in the currents all show the same trend, increasing firstly and gradually decreasing, whereas the current would increase sharply at each grouting point. The same

behavior was observed by Ou et al [22] and Mohamedelhassan and Shang [29]. The water electrolysis reaction produced large number of ions, increasing the conductivity of pore water at the beginning of the test, therefore, the current of all the tests firstly reached a peak and then dropped sharply due to the development of soil-contact resistance and electrode corrosion.

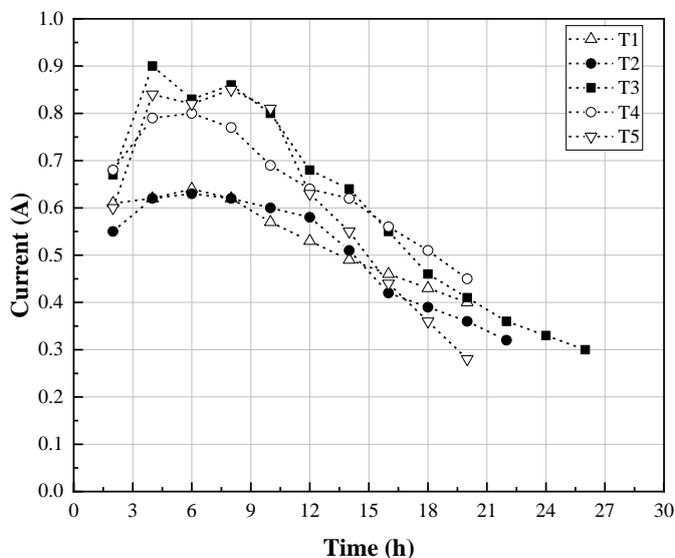


Figure 2. Variation of current with time during treatment for different injection procedures

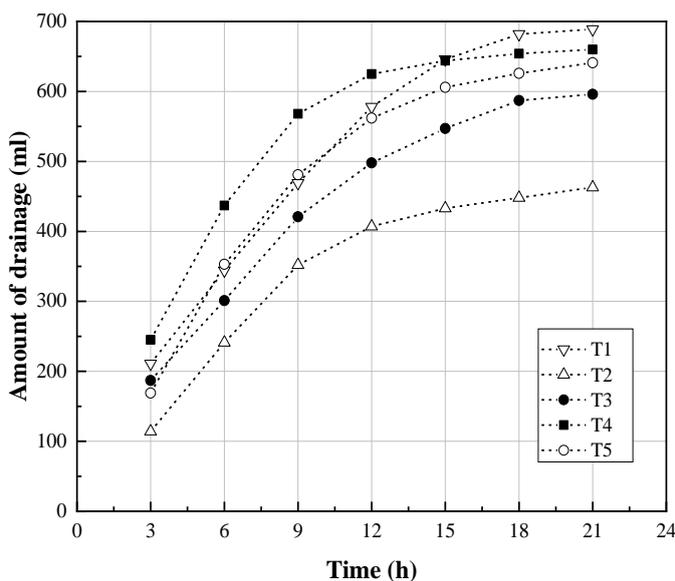


Figure 3. Variation of drainage volumes with time during treatment for different injection procedures

T3 and T5 presented peaks at 6 h of treatment with the increases of 30.88% and 29.51%, respectively. The chemical solutions, such as  $\text{Na}_2\text{SiO}_3$ , injected into the soil from the cathode have also contributed to the increase of current intensity. However, the current of T5 decayed rapidly after 13 h of the treatment, indicating that the  $\text{Ca}^{2+}$  and  $\text{SiO}_3^{2-}$  ions encountered in the soil mass under the electric field have undergone chemical reaction, producing cementation and precipitation, increasing the

resistance of soil, and decreasing the current continuously. The ionic concentration caused a high current. Reddy et al [30] reported that the decrease in ion concentration causes physicochemical changes, electro-migration, and electroosmotic flow. The precipitation reduced the ionic concentrations, significantly dissipating the electrical potential in this region [8, 31, 32].

### 3.2 Drained water

Fig.3 shows the evolution of the drainage volume with time during the testing period. Initially, in the first 9 h of treatment times, the volume of drained water increased linearly and then gradually slowed. All the samples injected with chemical solution had more dewatering efficiency than that in pure EO (T1). T4 resulted in the greatest dewatering efficiency due to injection of  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  at the anode. A maximum volume of 660 ml drainage was observed in T4. Compared with T5 and T2, the injection of  $\text{Na}_2\text{SiO}_3$  influenced the volume of drainage or dewatering efficiency in the process of electrokinetic stabilization. As describes in table 2, T5 achieved higher drainage than T2 because of the injection of large amounts of  $\text{Ca}^{2+}$  and  $\text{SiO}_3^{2-}$  from the anode and cathode, respectively. The current change in experimental T3 shows that injecting  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  from the anode and cathode could further improve the efficiency of electric chemical reinforcement compared to using a salt solution alone in the anode.

### 3.3 Energy consumption

The energy consumption of ECT is calculated using Eq (1) where  $U_i$  and  $I_i$  represent the effective voltage and the current, respectively, at a certain time  $t_i$ . Here, the energy consumption is proportional to the current under the same conditions of voltage and time. Fig 4 presents the variation of the energy consumption with time.

$$E = \sum U_i I_i t_i \quad (1)$$

Fig 4 shows that the energy consumption time curve presents linear distribution. There is little difference in the energy consumption between T2 and T1, and both are lower than the other three groups of tests, whereas the energy consumption of T3 is the highest, reaching approximately 0.49 kw/h, (Table 1), Energy consumption is a principal indicator of the electrochemical stabilization of soft soil and sometimes a decisive factor in its adoption. To compare the energy use efficiency of each group, the energy consumption coefficient is defined as:

$$(2) C = \frac{1}{Q_i} \int_{t_1}^{t_2} U I_\tau d_\tau$$

$Q_i$  is the volume of drainage between  $t_1$  and  $t_2$ .  $U$  is the applied electrical potential (V),  $I$  is the current between  $t_1$  and  $t_2$  (A), and  $C$  is the energy consumption per unit volume of drainage. The energy consumption coefficient marks the energy use efficiency, and the lower the energy consumption coefficient, the higher the energy use ratio. The energy consumption coefficient ( $C$ ), as defined by Eq (2) is calculated and plotted in Fig 5. Because the energy consumption is proportional to the electrification time, the time for calculating the total energy consumption was selected when the half-

hour drainage was zero. Fig 5 shows that the energy consumption coefficient of ECT is higher than that of EO without injecting a chemical solution under the same conditions, correlating well with the results obtained by [28]. The energy consumption coefficients of T2, T3, T4, and T5 are 38.3%, 59.6%, 10.6%, and 21.3% higher than that of T1, respectively. It can be concluded that electrokinetic stabilization requires more electrical energy than pure EO. The energy consumption coefficient of two types of solutions is lower than that of one type of solution, (Fig 5). In electrokinetic processes, the electrical conductivity is critical in energy consumption. [32, 33]. The injection of two chemical solutions is better than a single solution in improving the electrical conductivity of the soil. This can be explained by enough anions, maintaining the electrochemical process with high efficiency.

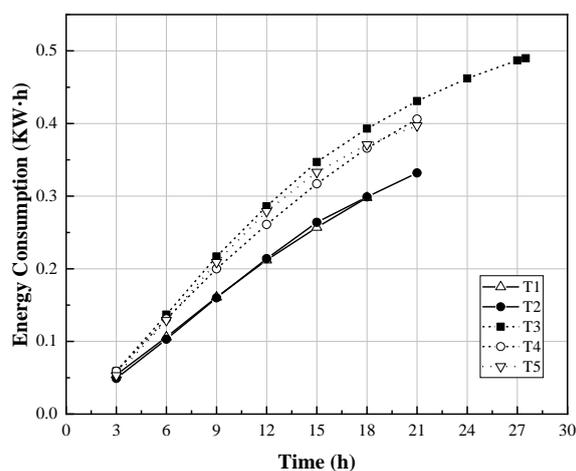


Figure 4. Energy consumption-time curves of each test

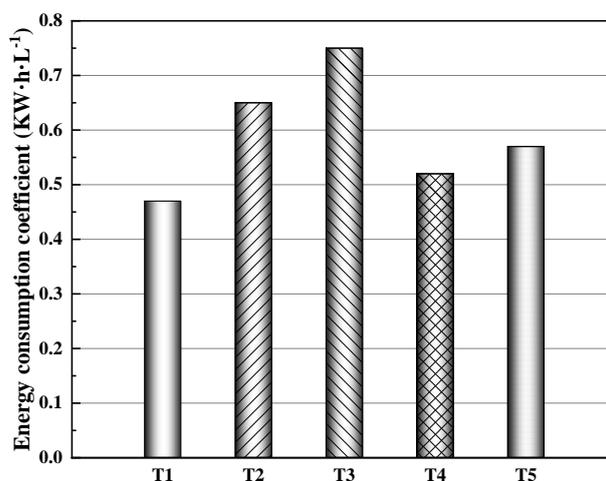
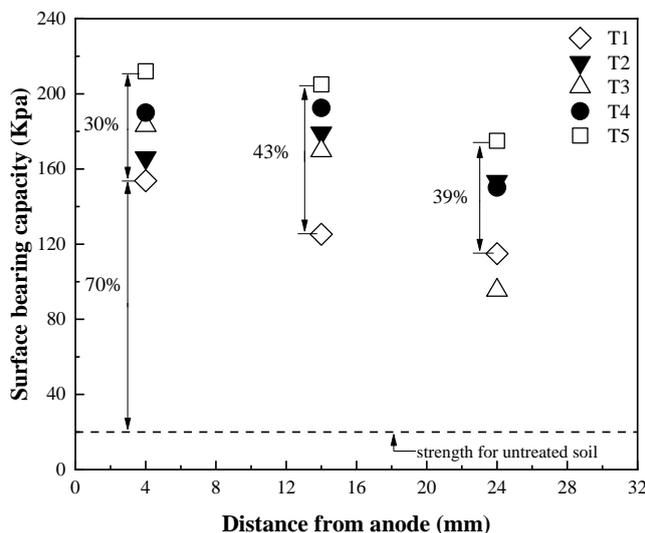


Figure 5. Energy consumption coefficient of different tests



**Figure 6.** Variation of strength with distance for different injection procedures

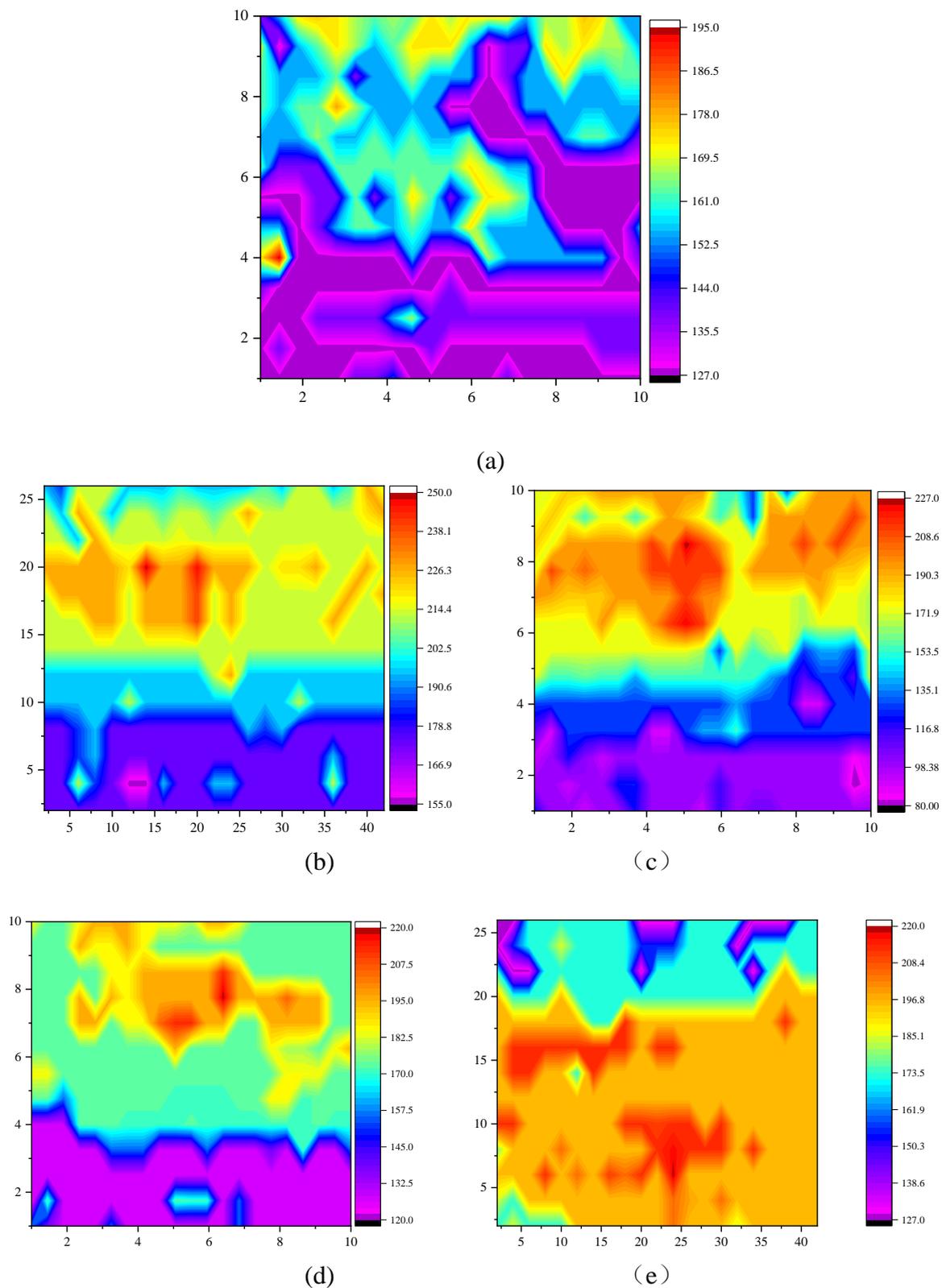
### 3.4 Bearing capacity

Several investigations have shown that, compared to the electroosmotic treatment, the strength of the soil still increases with time because of the processing of salt precipitation. To avoid the influence of soil moisture evaporation on the test results, the soil samples were sealed with fresh-keeping film and stored in the shade for one week and its 7-d surface bearing capacity were measured.  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  were the chemical solutions used for treatment. Fig. 6 shows the test results regarding the distance from the anode of 4 cm, 14 cm, and 24 cm samples. It can be seen from the figure that test T5 obtained the largest values, with 212 kPa in the anode zone. The improvement of the soil strength in the test with the injection of chemical solutions achieved larger values than the EO test, especially in the middle and cathode zones.

The strength increase consists of contribution of the pure EO and the injection with EOC [22]. Fig.6 shows the surface bearing capacity increase caused by EO and injection of  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  is 70% and 30% at 4 cm from the anode, respectively. Ozkan *et al* [20] categorized the increase of shear strength components into three components, including water content decrease, the electrochemical treatment and thixotropic effects. It was observed that the strength increases because the water content was 17%-22%, confirming that electrochemical treatment could be the dominant factor for the strength increase. The improvement obtained from T4 because of the injection of chemical solutions shows the highest values in each region, with values of 30%, 43%, and 39%, corresponding to the anode, middle, and cathode zones, respectively. The results are similar to the literature [22, 28]. Note that the surface bearing capacity increases in the middle zone achieved the highest values (43%). Compared to the pure EO of which the improvement area across the soil was limited in the anode zone, the test ECT enlarged the area including the middle and cathode zones.

The advantage of electrokinetic stabilization is that the ions can be uniformly transported to the soil and the structure of the soil can be rehabilitated without disturbance. Fig.7 shows that the surface bearing capacity of most of the area in the test T5 was greater than or equal to 173 kPa, whereas it was

127 kPa in the test T3, Although the same volume of  $\text{Na}_2\text{SiO}_3$  solution was injected into the cathodes of T5 and T3, the average surface bearing capacity in T5 was approximately 50, 60, and 70kPa higher than T3 regarding the cathode, middle, and anode zones, respectively.



**Figure 7.** Contour of strength:(a) T1 (b) T2 (c) T3 (d) T4 (e) T5

The improvement of soil strength is limited to a certain range around the anode after the EO treatment. To access the range of the effect of electrokinetic stabilization, the ratio of the area up to 180 kPa to the total surface area of the soil sample was calculated as T5 at 70.37%, T2 at 69%, T3 at 38.07%, T4 at 22.22%, and T1 at 1.6%. Electrokinetic stabilization can improve soil behavior (such as the Atterberg limits, swell potential, shear strength) uniformly in the range of specimens because dispenses the additive agent homogeneously [34].

Fig.7(d) shows that when  $\text{CaCl}_2$  was injected into the anode and  $\text{Na}_2\text{SiO}_3$  was simultaneously injected into the cathode, the improvement of soil was more uniform. Approximately 70.4% of the soil surface achieved a bearing capacity higher than 180 kPa. Furthermore, the cathode zone produced a larger value than other tests. Different injection procedures produce different effects, The general procedure is to inject  $\text{CaCl}_2$  first into the anode and then,  $\text{Na}_2\text{SiO}_3$  is injected, a suitable injection time was selected between the first and second inflection points of the total drainage and time curves [19], however, that time might vary among different soil types. Comparing test T4 and T5, we found that the simultaneous injection of  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  at the anode and cathode has some advantages. When  $\text{Ca}^{2+}$  was transported to the cathode, a large amount of  $\text{SiO}_3^{2-}$  reacted with  $\text{Ca}^{2+}$ . A pozzolanic reaction occurred, formed of cementing agents including calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) [35]. Therefore the T5 test obtained a much larger area than those of the T4 test.

#### 4. CONCLUSIONS

Electrochemical stabilization tests of marine clayey soils of Yingkou City (People's Republic of China) were conducted using two types of chemical solutions ( $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$ ) in different position of the electrodes. From the results, the following conclusions were dawn.

1. The injection of  $\text{CaCl}_2$  in the anode and  $\text{Na}_2\text{SiO}_3$  in the cathode was suitable operation procedure for the method of electrokinetic stabilization. The strength in the laboratory test obtained by this operation reached 212 kPa. The strength increase that was attributed to the injection of chemical additive in anode, middle, and cathode zones was 30%, 43%, and 39%, respectively.

2. The injection of two chemical solutions obtained more reduction of electrical conductivity in soil than the single one, confirming that the tests injected with chemical additives achieved higher strength improvement with lower power consumption than that of pure EO test.

3. The strength increase in both magnitude and uniformity were two remarkable characteristics of the electrokinetic stabilization because of the precipitation of  $\text{Ca}^{2+}$  or the formation of CSH with time after the treatment. The operational procedure introducing  $\text{CaCl}_2$  and  $\text{Na}_2\text{SiO}_3$  at the anode and cathode, respectively, obtained the most uniformed strength increase of approximately 70.4% of soil surface, achieving the bearing capacity higher than 180 kpa.

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