A study on electrokinetic stabilization of soft Bangkok clay using a physical model

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Abstract. Soft Bangkok clay, extensively distributed within Thailand's Chao Phraya Basin, presents significant geotechnical challenges due to its low shear strength, high compressibility, and considerable long-term settlement. Conventional ground improvement techniques commonly used in Thailand, such as preloading with surcharge, prefabricated vertical drains (PVDs), and vacuum consolidation with PVDs, have proven effective in many applications. However, the application of electrokinetic stabilization remains limited in practical engineering projects within the country. This study investigates the potential for electrokinetic stabilization to enhance the engineering properties of soft Bangkok clay, focusing on improvements in shear strength, compressibility, and long-term settlement, as well as assessing its environmental impacts. The research examines the fundamental mechanisms involved electroosmosis, electrolysis, electrophoresis, and electromigration through small-scale physical modeling and conventional laboratory testing. The methodology includes developing a small-scale physical model and evaluating both basic and mechanical properties of soil samples before and after electrokinetic stabilization. The experimental program involves determining initial properties such as water content, Atterberg limits, pH, unit weight, specific gravity, compressibility using the oedometer test, and shear strength using the unconfined compression test. During the electrokinetic process, settlement, drained water volume, electrical current, voltage, pH variation, and surface cracking are continuously monitored. The findings aim to demonstrate electrokinetic stabilization as an effective alternative for ground improvement in confined urban areas where conventional methods are impractical, thereby contributing to safer construction and more efficient land utilization in Bangkok soft clay regions.

1 Introduction

Soft Bangkok clay, extensively distributed within Thailand's Chao Phraya Basin, presents significant geotechnical challenges due to its high compressibility, low shear strength, and susceptibility to long term and differential settlement [1, 2]. These characteristics often lead to damage to infrastructure, particularly for structures supported by shallow foundations. Common examples observed in Thailand include road pavements, industrial floor slabs, taxiways, runways, and transition zones between shallow and pile foundations, such as bridge approach sections and pier structures located within roadway areas. Examples of such damage are illustrated in Fig. 1, highlighting the severity of differential settlement in practice. In many situations, insufficient soil bearing capacity makes shallow foundation construction impractical, leading to increased construction costs when pile foundations are adopted as an alternative solution. In addition, differential settlement may impair serviceability and raise safety concerns during operation. Ground improvement of soft clay prior to construction is therefore necessary to enhance soil shear strength and to reduce future settlement.

Several ground improvement techniques are commonly applied in Thailand. Preloading uses temporary surcharge loads to accelerate consolidation through pore water dissipation. Prefabricated vertical drains shorten drainage paths and further accelerate consolidation, while vacuum consolidation induces consolidation through applied suction with reduced surcharge requirements [3]. Despite their effectiveness, these methods have limitations in areas with existing operating facilities, limited available space, or where long improvement periods are not feasible. [4]

Electrokinetic stabilization has emerged as an alternative technique for improving soft clay. The method accelerates pore water migration under an applied electric field, thereby enhancing drainage, inducing soil densification, and improving soil mechanical properties. It is particularly suitable for low permeability soils such as clay and enables ground improvement at depth with limited surface disturbance [3, 4]. The technique can also be applied in confined or difficult to access areas. However, previous studies have mainly focused on soil decontamination, dewatering, and strength improvement [5, 6], while studies investigating soil behavior and factors influencing settlement during the electrokinetic process remain limited [7, 8], despite settlement being closely

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associated with soil densification. Furthermore, this technique has rarely been applied in practical projects in Thailand.

Therefore, this research aims to investigate the time dependent behavior of soil during electrokinetic stabilization using a small-scale physical model and basic laboratory testing. The study focuses on the relationships among settlement, water drainage, chemical property changes, electrical energy variation, and fundamental soil properties, including shear strength characteristics. The outcomes of this study are expected to support the practical application of electrokinetic stability for improving soft clay stability in Thailand.

(a)

(b)

Fig. 1. Examples of infrastructure damage caused by differential settlement observed in Bangkok, Thailand. (a) bridge approaching unit, (b) pier structures located within roadway areas.

2 Theory of electrokinetic stabilization

Use of the term “electrokinetic” in relation to soil–water systems refer to the relative movement between soil particles and the liquid phase under the influence of an electric field [3]. Electrokinetic stabilization involves installing electrodes within a continuous soil-water system and applying a direct current to generate an electrolytic cell. The electrode connected to the negative terminal acts as the negative cathode, while the electrode connected to the positive terminal acts as the positive anode. Electrons move from the anode to the cathode, and changes occur in the soil due to electrical phenomena within the system, particularly in clay.

Clay particles carry a negative surface charge due to isomorphous substitution. As a result, a diffuse double layer of positive ions forms around the particle surface. This double layer consists of the Stern layer, where positive ions are firmly attached to the particle surface, and the diffuse layer, where the attractive force decreases with increasing distance and positive ions are relatively free to move. Beyond this region is the free water layer, where positive and negative ions have equal concentrations [9]. When an electric potential is applied to wet soil mass, positive ions in the diffuse layer migrate toward the negative cathode and drag free water along with them. Consequently, water moves from the positive anode to the negative cathode. This process, known as electroosmosis, reduces soil moisture content, increases soil strength, and decreases compressibility similar to standard consolidation [3, 10].

In addition to electroosmosis, other electrokinetic phenomena occur when an electric current is applied to saturated soil [4]. Electrophoresis refers to the movement of freely moving negatively charged clay particles toward the positive anode, typically occurring in a soil suspension, while free positively charged ions migrate toward the cathode. Electromigration describes the movement of dissolved ions under the induced electric potential, resulting in the transport of solutes such as salts during the electrokinetic process. Furthermore, electrolysis of water occurs due to electron transfer at the electrodes, leading to redox reactions. Oxidation occurs near the anode where water molecules lose electrons, while reduction occurs near the cathode where water molecules gain electrons. These reactions create an acidic environment near the anode and an alkaline environment near the cathode, contributing to physicochemical changes in the soil during electrokinetic treatment. Previous studies have shown that electrokinetic stabilization can produce a greater increase in strength than standard consolidation due to physicochemical changes occurring within the soil by positive ions releasing at the corroded anode [3, 6].

3 Soil specimens

Very soft Bangkok clay was selected as the soil specimen for the electrokinetic stabilization experiment due to the suitability of its physical and chemical properties for electrokinetic processes. The soil was collected at a depth of 1.5 m below the ground surface using borehole drilling within the very soft clay layer in Samut Prakan Province, Thailand, as shown in Fig. 2. This clay is widely recognized for its high compressibility, high natural water content, and low shear strength. The initial physical properties of the collected soil include a total unit weight of 15.55 kN/m^3, natural water content of 78.95%, specific gravity of 2.75, liquid limit of 66.31%, Plasticity Index of 40.64%, and shrinkage limit of 14.38%. Based on these properties, the soil is classified as high plasticity clay (CH). The measured pH value of the soil is 8. At this stage, the undrained shear strength could not be determined because the specimen was unable to maintain its shape due to the very high-water content.

Fig. 2. Very soft clay specimen collection in Samut Prakan Province, Thailand.

4 Physical model testing

4.1 Model apparatus

The physical model used in the electrokinetic stabilization experiment is illustrated in Fig. 3. The model is made of acrylic material and is divided into three main parts separated by circular perforated walls on both the anode and cathode sides. The central part contains the soil specimen. Polyurethane foam was installed at the base to seal the joints between the walls and the model base, preventing leakage. It also serves to elevate the specimen above the drainage outlets, thereby facilitating outward flow toward the anode and cathode chambers and preventing backflow into the central soil region. A 0.3 mm thick copper sheet is installed at both the cathode and anode sides in contact with the soil specimen. A nonwoven geotextile is subsequently installed to allow water flow while preventing particle migration. The power supply is connected to the copper sheet to generate electrolytic cell, with the negative cathode located on the side of the copper sheet containing drainage holes to allow the outflow of water, and the positive anode located on the opposite copper sheet without holes.

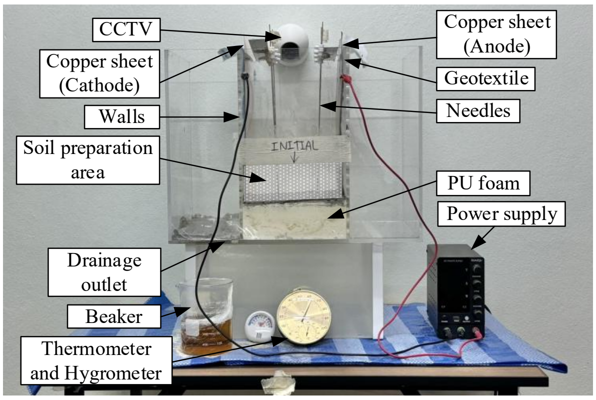

Fig. 3. Physical model used in the electrokinetic stabilization experiment.

4.2 Experimental methodology

The experimental methodology is described in this section (Fig. 4). First, soil samples collected from the field were subjected to laboratory testing to determine their initial index and physical properties. The index properties included moisture content, dry density, specific gravity, Atterberg's limits, and soil pH. The physical properties were determined through unconfined compression and consolidation tests.

Thereafter, the specimens were prepared within the physical model by placing three layers of clay in the central section of the electrokinetic system apparatus. Each layer consisted of 2.13 kg of clay and was subjected to 150 controlled blows to achieve a uniform initial density and consistency throughout the specimen. This procedure was adopted to ensure uniformity of the remolded saturated samples. The final specimen height was 13 cm. After specimen preparation, the index and physical properties were tested to evaluate any changes resulting from the preparation process.

Following this, two experimental cases were established to investigate the behaviors of electrokinetic stabilization. Case 1 was conducted without electrical input as a control condition to assess changes in soil behavior induced by self-weight and surface evaporation, independent of any electrokinetic effects. Case 2 was conducted using a constant applied voltage of 5 volts to investigate electrokinetic stabilization behavior at room temperature. Surface settlement, visible surface cracks, drained water volume, electric current, pH of drained water, and pH of the soil water system were monitored at 1, 2, 4, 8, 15, 30, and 60 minutes, followed by 2, 4, 8, and 24 hours, and subsequently monitored daily for 7 days or until no further change in electric current was observed.

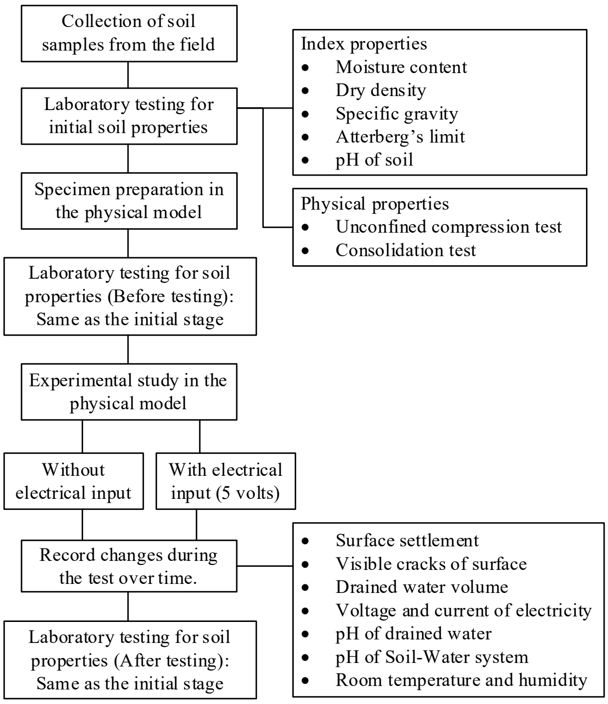

Fig. 4. Experimental methodology.

For surface settlement monitoring, the specimen surface was divided into 2 zones. Zone 1 and Zone 2 represent the soil regions near the cathode and anode, respectively. Needles were installed at the designated zones to measure settlement in each area to evaluate differences in settlement behavior between zones. Steel bars were fixed at the top of the apparatus to provide reference levels throughout the experiment and to maintain the needles in position. A beaker was placed beneath the drainage outlet of the model to measure the volume of drained water. The soil pH in each zone and the drained water pH were measured using indicator paper. To facilitate continuous monitoring, a CCTV system was installed to record visible surface cracks, temperature, and volume of drained water during each stage of the experiment.

After completion of the monitoring period, the index and physical properties of the tested specimens were re-evaluated to determine changes resulting from both experimental cases. Furthermore, electrode weight changes were measured to access corrosion and the formation of new substances during the electrokinetic process.

5 Results and discussion

5.1 Self-weight compression and surface evaporation (Case 1)

Experimental Case 1 was conducted without electrical input to evaluate soil behavior resulting from specimen self-weight and surface evaporation. The results show that no surface settlement was observed during the initial stage until approximately 1,000 minutes. Small settlements then began to occur and gradually increased, becoming nearly constant at approximately 1.02 mm after about 7,000 minutes (Fig. 5a). Throughout the test, no water drainage, expressed as volumetric water content (Fig. 5b), was observed in the beaker. In addition, the soil pH in all zones remained constant at 8, which was the same as the initial condition. The clay surface exhibited minor shrinkage and hairline cracks. These cracks were shallow and appeared mainly at the surface and near the walls of the model. The clay remained saturated beneath the surface, and no significant cracking was observed within the soil mass. Furthermore, the index properties and physical properties showed no significant change (Figs. 8-13).

Based on the above observations, the settlement and minor surface hairline cracks observed in Case 1 can be attributed to self-weight compression and minor evaporation rather than the water drainage, as the very soft clay exhibited extremely low hydraulic conductivity without electrical input. Consequently, no significant changes were observed in the index and physical properties of the soil.

5.2 Electrokinetic stabilization behavior (Case 2)

Experimental Case 2 was conducted under a constant applied voltage of 5 volts to evaluate the effectiveness of electrokinetic stabilization until a stable improvement trend was achieved. As illustrated in Fig. 5, during the early stage from 0 to 130 minutes, the clay specimen exhibited no settlement and no water drainage, indicating that pore water movement had not yet begun to drain.

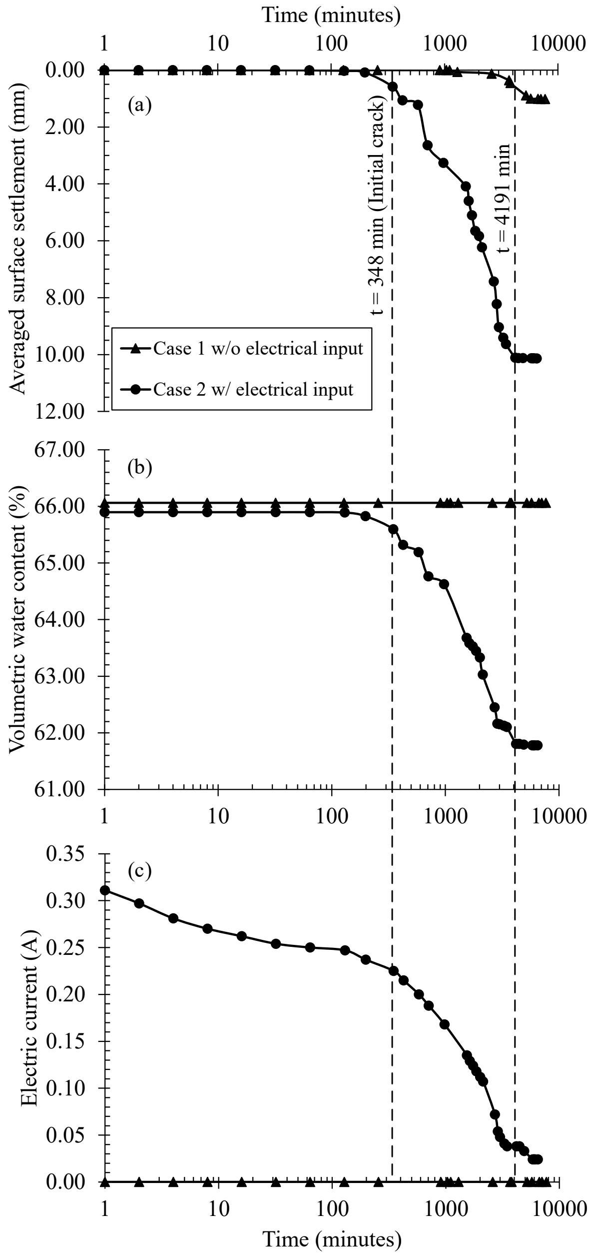

Fig. 5. Variation of (a) averaged surface settlement, (b) volumetric water content and (c) electrical current with time during the electrokinetic process.

Changes in settlement, water drainage and electrical current were first observed at approximately 130 minutes. Both settlement and water drainage then began to increase more rapidly after 198 minutes. The first visible crack, as shown in Fig. 6, subsequently appeared at approximately 348 minutes, coinciding with the first abrupt change in settlement, the volume of drained pore water collected at the negative cathode, and the electrical current.

After crack initiation and subsequent propagation (Fig. 6), settlement and the volume of drained pore water at the negative cathode increased significantly, while the electrical current decreased sharply. During this period, the collected water gradually darkened to a strong brownish orange color, indicating the migration dissolved ions with the pore water. Subsequently, the settlement, drainage, and current curves began to flatten at approximately 4191 minutes (Fig. 5) while crack widening ceased (Fig. 6), indicating that the soil became drier and more electrically resistant as pore water was drained.

The soil pH remained slightly alkaline, with the values of approximately pH 8 near the positive anode and pH 9 near the negative cathode, consistent with the expected electrochemical reactions associated with water electrolysis and ionic migration. The collected drainage water also exhibited an alkaline pH of approximately 9, indicating the accumulation of hydroxide ions (OH^-) near the cathode due to electrochemical reduction reaction.

In addition, solid salt deposits were also observed around the beaker. This stage was identified as the optimum time for electrokinetic stabilization, defined by the flattening of the three observed indicators, namely settlement, drained water, and electrical current. Beyond this point, although voltage was still applied, no significant increase in settlement or drainage was observed. Continued operation would therefore result only in unnecessary energy consumption and additional electrode corrosion without further improvement. For this reason, the voltage supply was terminated at the optimum stage.

The final settlement of approximately 10.14 mm in Case 2 under a 5 V electrical input was significantly greater than the negligible settlement observed in Case 1 without electrical input under the control condition. The electrodes provided clear evidence of electrochemical activity. The copper cathode exhibited slight darkening due to reduction reactions, with a mass increase of 9.48%, whereas the copper anode experienced significant corrosion with visible greenish blue deposits due to oxidation, resulting in a mass loss of 4.13% (Fig. 7).

At the end of the experiment, pore water migrated from the positive anode toward the negative cathode due to electroosmosis, resulting in significant settlement (Fig. 5a), a decrease in moisture content (Fig. 8) and an increase in dry density on the anode side (Fig. 9). The specific gravity of the soil on both the anode and cathode sides decreased significantly compared with the initial condition. However, the specific gravity on the anode side remained slightly higher than that on the cathode side (Fig. 10), indicating electroosmosis and ion migration, which promoted the dissolution and transport of salts and heavier compounds from the clay structure.

Electroosmosis and physicochemical reactions at the corroding anode significantly reduced the moisture content near the anode, resulting in soil settlement, an increase in dry density, and a significant improvement in unconfined compressive strength, as shown in Fig. 11.

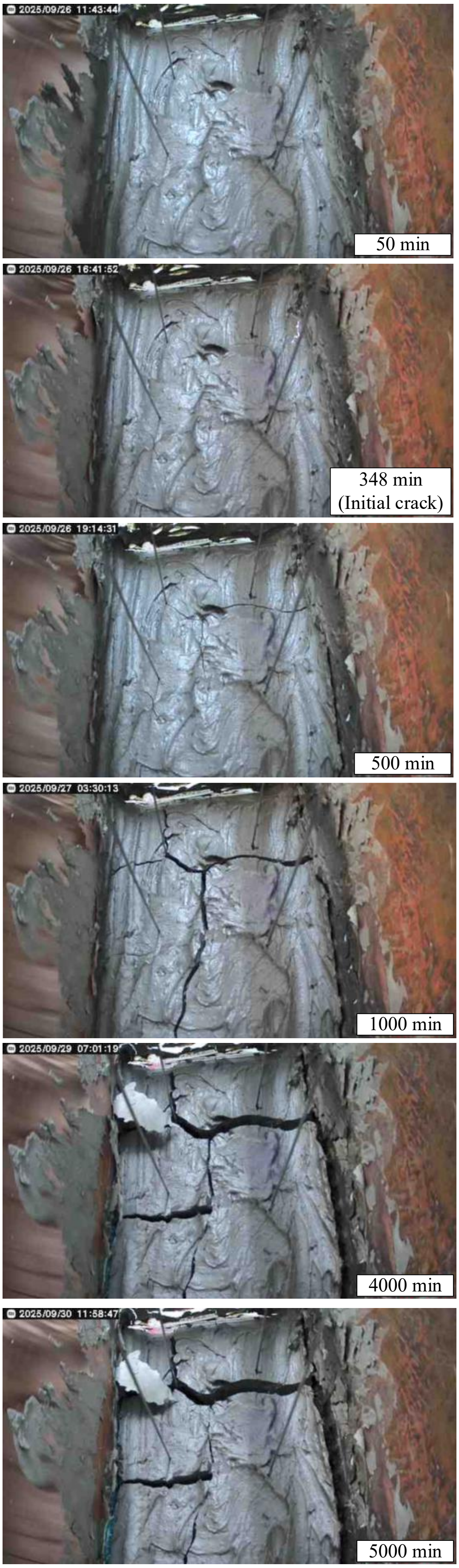

Fig. 6. Surface crack development with time during electrokinetic process.

In addition, as shown in Fig. 12, the Plasticity Index increased on the anode side, while it decreased on the cathode side after the electrokinetic process. The increase in plasticity at the anode is likely associated with physicochemical changes, including possible alterations in soil structure under acidic conditions. In contrast, the decrease in plasticity at the cathode may be attributed to alkaline conditions and ion accumulation, which can promote particle aggregation and reduce plasticity. These results suggest that the variation in Plasticity Index is influenced by electrochemical conditions.

As shown in Fig. 13, the shrinkage limit on the anode side remained approximately unchanged, indicating that the intrinsic shrinkage characteristics of the soil were largely preserved despite significant moisture loss and densification. In contrast, the shrinkage limit on the cathode side decreased substantially, suggesting a change in soil structure. This reduction is attributed to flocculation and changes in the diffuse double layer under alkaline and high ionic conditions. These findings indicate that shrinkage behavior is governed not only by moisture content but also by physicochemical and structural changes induced during electrokinetic process.

Furthermore, the one-dimensional consolidation test results show that the compression index decreased from 0.367 to 0.263 after the process, indicating a reduction in soil compressibility. This result is consistent with the observed increase in dry density and strength.

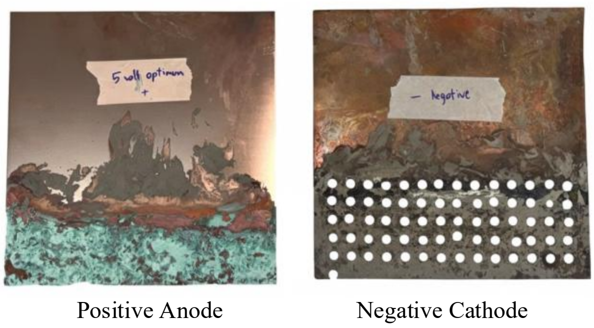

Fig. 7. Appearance of the copper sheet electrodes after the test.

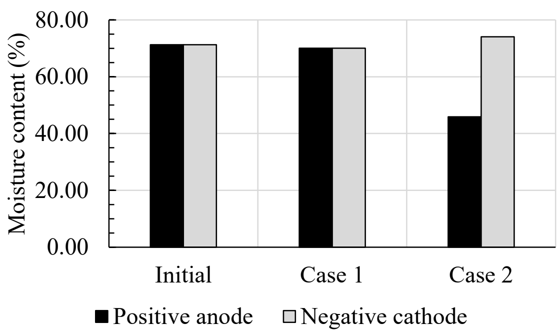

Fig. 8. Soil moisture content under the initial condition, Case 1, and Case 2 at each electrode side.

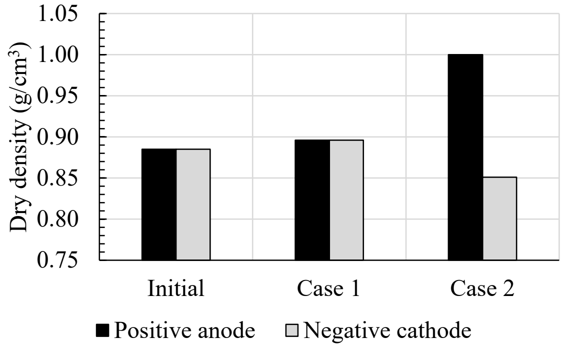

Fig. 9. Dry density under the initial condition, Case 1, and Case 2 at each electrode side.

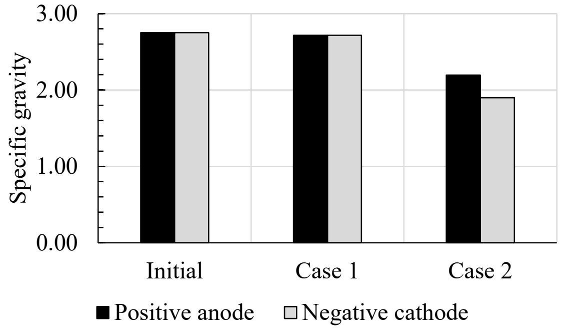

Fig. 10. Specific gravity under the initial condition, Case 1, and Case 2 at each electrode side.

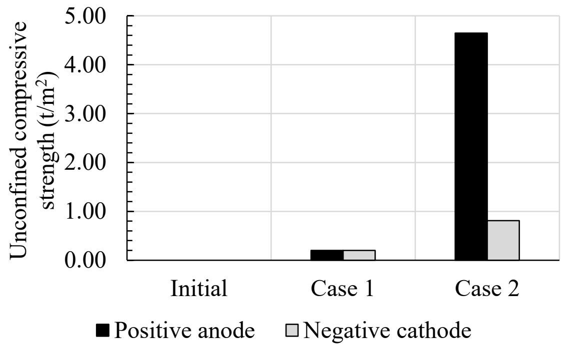

Fig. 11. Unconfined compressive strength under the initial condition, Case 1, and Case 2 at each electrode side.

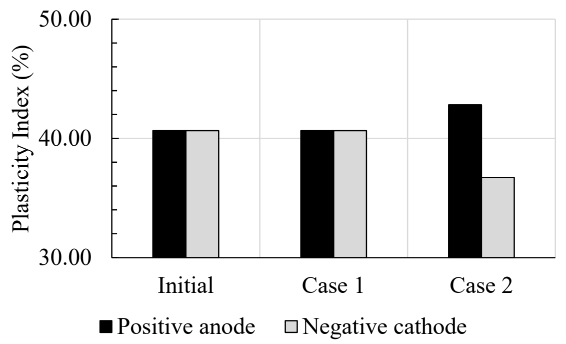

Fig. 12. Plasticity Index under the initial condition, Case 1, and Case 2 at each electrode side.

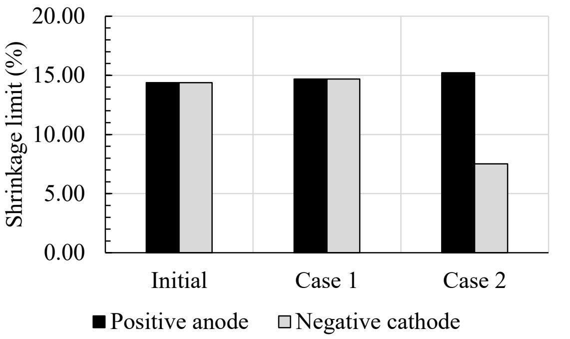

Fig. 13. Shrinkage limit under the initial condition, Case 1, and Case 2 at each electrode side.

6 Conclusions

This study investigated the time dependent behavior of very soft Bangkok clay during electrokinetic stabilization using a small-scale physical model and laboratory testing. The results demonstrate that electrokinetic stabilization can effectively accelerate pore water migration, reduce moisture content, and improve the engineering properties of very soft clay.

Under an applied voltage of 5 V, pore water migrated from the positive anode toward the negative cathode due to electroosmosis, resulting in significant settlement and drainage. The onset of settlement and drainage coincided with changes in electrical current and the initiation of surface cracking, indicating the transition from a fully saturated condition to dewatered and densified state. The improvement process reached an optimum stage when settlement, drainage volume, and electrical current became stable, suggesting that continued electrical input beyond this point provided minimal additional benefit while increasing energy consumption and electrode corrosion.

Electrochemical reactions played an important role in modifying the soil system. The alkaline condition observed near the cathode confirmed the accumulation of hydroxide ions produced by reduction reactions, while corrosion at the anode indicated oxidation processes and ion release into the soil water system. Ion migration and electroosmosis contributed to the dissolution and transport of salts and heavier compounds from the clay structure, leading to changes in soil structure. This resulted in a reduction in measured specific gravity, Plasticity Index and shrinkage limit, especially on the cathode side. The soil near the anode experienced a reduction in moisture content, leading to increased dry density, a significant improvement in unconfined compressive strength, and a reduction in compressibility, while maintaining its intrinsic shrinkage characteristics. These findings confirm that electrokinetic stabilization improves soil strength through densification, moisture reduction, and physicochemical changes.

The experimental results indicate that electrokinetic stabilization has strong potential as an alternative ground improvement technique for very soft Bangkok clay, particularly in areas where conventional methods are constrained by limited space. Monitoring settlement, drainage, and electrical current simultaneously provides a practical indicator of the optimum improvement duration.

However, several aspects require further investigation before practical implementation. Future studies should examine the variation in soil strength with distance from the anode and cathode, since although higher strength was observed near the anode, the presence of oxide products may affect long term performance and suitability for construction. The durability of improved soil under rewetting conditions should also be evaluated, as groundwater fluctuations or rainfall may influence the retained strength after treatment. In addition, as the present study is based on limited experimental data, further experimental investigations are required to verify these findings and establish reliable trends.

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