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Application of electro-osmosis method on Baghdad soft clay shear strength using vane shear test and pile installation efficiency

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A B S T R A C T

This paper examines the characteristics of soft clayey soils prevalent in the central and southern regions of Iraq. The study focuses on assessing the impact of electro-osmosis (E.O.) on both the shear strength of these soils and the efficiency of pile driving, including the installation of experimental piles. The investigation employs laboratory equipment and locally sourced Baghdad soft clay soil to conduct a comprehensive test program. This program encompasses conventional soil tests and utilizes two specialized soil boxes designed for E.O. to collect essential parameters for pile prototype installation. The primary objective is to explore how E.O. affects the pile driving process. The shear strength was evaluated through four vane shear tests, with vertical E.O. voltage applied at varying depths. The findings indicate that the shear strength in anode regions exceeds control results by up to 100%, with a decrease in strength observed as testing moves towards the cathode. Another significant finding is the Percentage Reduction in Blows, which typically ranges from 65% to 90%. These outcomes were derived from four tests conducted at a soil water content of 25%.

1. Introduction

Light brown silty clay soils, which are medium to soft, are predominant at depths of up to 10 meters below ground level across most of the middle and southern regions of Iraq. These soils exhibit particularly challenging behavior in response to the structural loads imposed by construction activities. Given their weak and soft nature, numerous studies have focused on methods for improving and stabilizing such soils. Electro-osmosis (E.O.) is recognized as an effective method for accelerating the consolidation and strengthening of soft, saturated clayey soils, as depicted in Fig. 1.

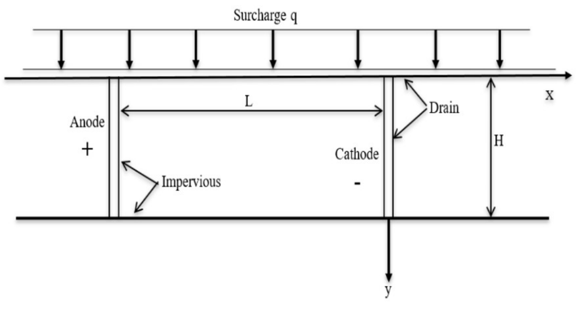

Figure 1. Schematic representation of electro-osmosis (E.O.) elements during the consolidation process (redrawn by author) [1].

By applying an appropriate electrical field through soil using electrodes, the pore water is directed towards the cathode, a movement primarily governed by the electrical intensity [2]. For high plasticity fine soils treatment within lime and fly ash, the structure levels between fly ash and lime causing the compressibility index of the mixture alter. The ideal mixture happens in trials with a fly ash content of 25% [3]. In general, inserting deposits into minor fragments, holes, impermeable soil media, areas of water drip, setting cracks or faults in material, and filling places under metal seats or excavation anchors are commonly pragmatic because of the excessive strength and workability of the cement in these constituents [4]. Abdulameer after exploring many forms of concrete reservoirs under seismic load bearing in mind soil-structure interface, he found that its desirable to use rounded reservoirs because they have a high confrontation to shear forces, bending moments, pressures, adjacent strength, and have slight soil consolidation compare with the other tanks [5]. Electro-osmosis (E.O.), as a soil stabilization technique, has gained global recognition due to its ability to dewater and strengthen fine-grained soils. The underlying processes, including electrophoresis, di electrophoresis, electrokinetic migration, and electro hardening, play crucial roles in enhancing soil properties. These processes are influenced by various factors such as soil conditions, the presence of mobile ions, pH levels, and the extent of the diffused double layer [6]. A comprehensive review of the literature reveals three main categories of applications for E.O. in soft clayey soils. The first category involves using E.O. to enhance the properties of weak soils [7, 8]. The second category focuses on the removal of harmful substances from contaminated soils [9]. Various researchers have explored the impact of inorganic coagulant pre-conditioning on sludge through the application of electro-dewatering methods [10]. Additionally, Ruoxuan et.al [11] deals with the assessment of energy consumption within large-scale three-dimensional electro-osmotic-hydraulic systems for sludge consolidation has been considered. Qi et.al [12] studied on vacuum electro-osmosis (E.O.) has been conducted to investigate the interplay between the reduction and remediation of contaminants in dredged sediments from Tai Lake.

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Nomenclature

ISS	Interfacial Shear Strength	*Sku*	Kurtosis
SBS	Styrene-Butadiene-Styrene	*Sdq*	Root Mean Square Slope
PLA	Polylactic Acid	*Sdr*	Developed Interfacial Area Ratio
MTD	Mean Texture Depth	*S*	Spatial Surface Area
3D	Three-Dimensional	S'	Horizontal Projected Area
HMA	Hot Mix Asphalt	*DC*	Degree Of Curvature
NMAS	Nominal Maximum Aggregate Size	S	Spatial Surface Area
AC	Asphalt Content	*SCRB*	State Corporation For Roads And Bridges
VS	Volume Of Sand	$CRS-1$	Cationic rapid setting emulsion
As	Total Material-Covered Surface Area	$CSS-1h$	Cationic slow setting -hard asphalt
Sa	Arithmetic Mean Height	$RC70$	Rapid curing cut back at viscosity 70
Sq	Root Mean Square Height	$HRC-70$	Rapid curing -hard asphalt at viscosity 70
Sz	Maximum Height	$MS4-70$	Rapid curing - 4% modified SBS asphalt at viscosity 70
Ssk	Skewness	$MSP5-70$	Rapid curing - modified asphalt with SBS and PLA at a viscosity 70

This approach has proven effective in transporting and discharging pollutants, achieving optimal remediation outcomes. The removal rates at the anode and cathode were reported to be 45.1% and 50.0%, respectively. Furthermore, Paixão et.al. [13], deals with soils contaminated with petroleum which can be effectively remediated using the electrokinetic process (EK), as demonstrated. The third category revealed by Mohamedelhassan and Shang [14] researched on encompasses a discussion of various E.O. parameters, including probe materials, addition of electrolyte materials to boost E.O. efficiency and the impact of current intermittence, the duration of E.O. application [15], then consider electrodes (probes) configuration or pattern [6], direct current (D.C.) elements [16], characteristics of interfacial resistance [17], and the use of E.O. to increase pile capacity or to employ E.O. probes as piles to support loads [18]. Numerous studies have documented improvements in the shear strength of soft clayey soils due to the application of direct current D.C. These studies consistently report significant enhancements in soil cohesion, increases in the undrained shear strength (Cu), and reductions in soil water content (ω), all achieved within a short timeframe of less than half a day. This study, for instance, records a 172% improvement in Cu for Gloucester clay, as illustrated in Fig. 2.

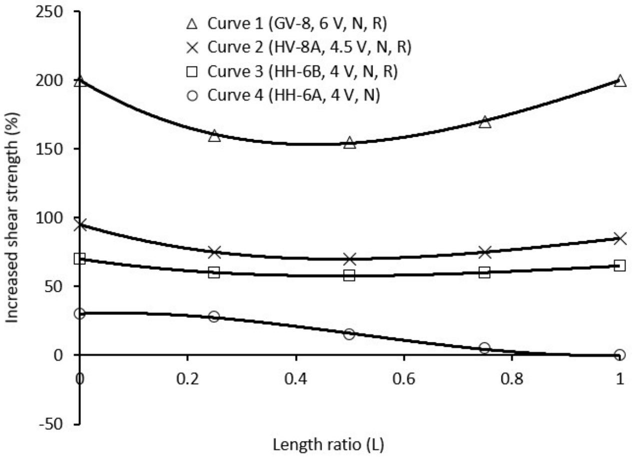


Figure 2. Distribution of shear strength increase of various samples after treatment (redrawn by author) [19].

Additionally, numerous researchers have confirmed the application of electro-osmosis (E.O.) can increase the undrained shear strength (Cu) of soils. This enhancement occurs as a result of the movement of moisture through the soil towards the negative electrode [20–23]. There are various studies which have been performed on the effect of E.O. stabilization, as to improve the bulk of the ultimate capacity of the soil [24], Furthermore, the impact of electro-osmosis (E.O.) on soil settlement was evaluated through laboratory experiments. The study discovered that the application of direct current (D.C.) voltage to gypsiferous soil significantly influences the soil's surface settlement over time [25]. The practical problems in foundation engineering and earthwork for which E.O. could have been considered [26]. L. Bjerrum and co-workers studied the use of electro-osmosis in solving a problem of shallow foundation in Norwegian quick clay. In their paper, they showed an example where the strength Quick clay with a strength of far less than 1 ton/m^2 is electro-osmosed up to the strength of 4 $tons/m^2$ as average with their own test results as shown in Fig. 3. This study intends to provide the characteristic view of the impact of the electro-osmotic treatment on the soft clay from the treatment process and on excavation site observation. These tests involve porewater pressure and settlement readings at different depths and laboratory testing on how the treatment changed the properties of the clay [20].

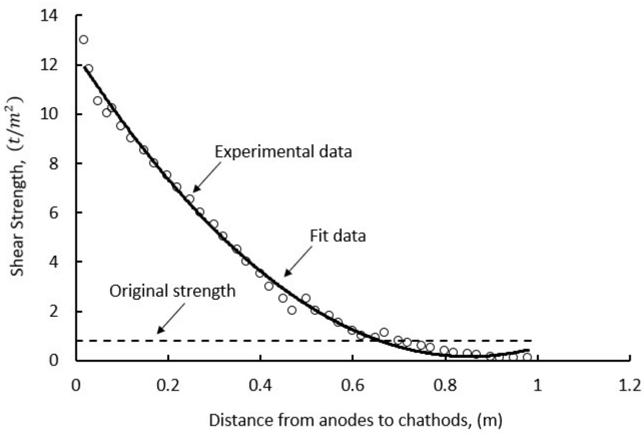


Figure 3. Results of vane borings and sampling carried out at a depth of 4.5 m below ground surface during the excavation period (approx. 50 days after the end of the osmosis treatment)(redrawn by author) [20].

Assessments of the mechanical and chemical properties of expansive soils following the application of electro-osmosis (E.O.) revealed a reduction in swelling potential by 83% and a decrease in pH levels. Additionally, the process resulted in an remarkable 800% increase in unconfined compressive strength [27], in an alternative method aimed at enhancing the shear strength of clayey soils, sugar was employed as an additive to cement. Results indicated that incorporating 1% sugar led to a notable improvement in soil strength. However, this enhancement diminished slightly when the sugar content was increased to 2%. The data suggest an inverse relationship between the percentage of sugar added and the improvement in soil strength. Specifically, adding 1% sugar to the cement resulted in approximately a 30% increase in soil strength compared to using the same percentage of cement alone [28]. An alternative approach to pile construction has been explored, leveraging the application of electro-osmosis (E.O.) in various ways. A noteworthy study demonstrated that incorporating electrodes as electro-osmotic piles can effectively serve as vertical drains. This method results in a substantial improvement in the overall strength and stability of the soil layers [9], This study investigates the use of electro-osmosis (E.O.) to enhance both the capacity and installation efficiency of piles in both offshore and onshore environments. It specifically examines the capacity of friction piles in varved clay that has been improved by E.O. The research builds on previous work on the electrical hardening of clays surrounding aluminum friction piles. An additional investigation, comprising two controlled studies, was conducted to explore the utilization of vertical electro-osmosis (E.O.) within a pile model embedded in clayey soils. The findings indicate that the implementation of vertical E.O. can enhance the overall pile capacity by approximately 17% [29, 30]. Soderman and Milligan's data on treated piles, which were subjected to E.O. for an extended period (three decades), show that the capacity of friction piles increased significantly. Notably, piles retested after 33 years maintained their enhanced capacity, with some achieving a doubling of their initial load-bearing capacity (from 300 kN to 600 kN). Fig. 4 illustrates the observed load on a tested pile after 34 days, highlighting the enduring benefits of E.O. treatment on pile capacity in soft varved clay and loose silts extending to a depth of 100 meters [31]. The general analytical solutions for one-dimensional large strain consolidation of soft soils under electro-osmosis–surcharge preloading study were conducted. A novel analytical solution for the one-dimensional large strain consolidation of soft soils under electro-osmosis (EO) and surcharge preloading conditions is presented. This solution is derived from a governing equation, which is established based on certain assumptions. For the first time, we propose a general analytical solution employing algebraic transformation and separation of variables methods. Specific analytical expressions are developed for several typical scenarios encountered in foundation treatment. The accuracy of these solutions is validated by comparing them with both existing analytical solutions and finite difference solutions.

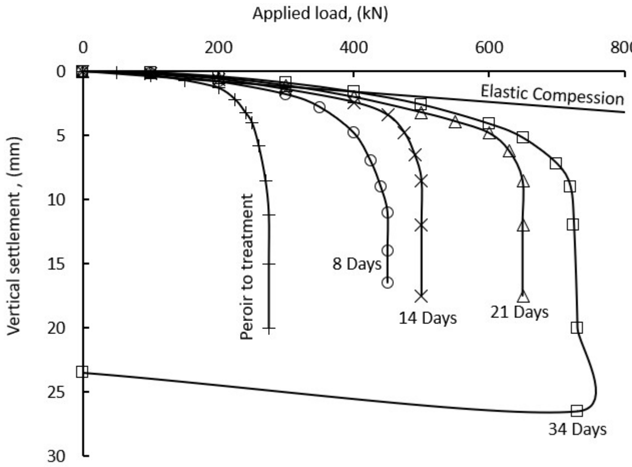


Figure 4. static axial pile load test on pile of different days of treatment (re-drawn by author) [31].

Additionally, the influence of effective voltage, the E.O. conductivity to hydraulic conductivity ratio, and the volume compressibility coefficient on consolidation behavior is analyzed using the proposed analytical solutions. The simplicity and practicality of these solutions make them suitable for analyzing one-dimensional large strain consolidation under E.O. and surcharge preloading conditions [32]. Fig. 5 presents a comparative analysis between the proposed analytical solution for large strain conditions and the existing solution for small strain conditions. As depicted in the figure, when the effective voltage is low, both the average consolidation degree as a function of settlement over time Fig. 5a and the depth distribution of excess pore water pressure (EPWP), Fig. 5b exhibit similar trends under both large and small strain models. This observation confirms the validity of the analytical solution introduced in this study [32]. The aim of this research is to investigate the effectiveness of improving the properties of clayey Baghdad soil by using D.C. and EO (Electro-osmosis) treatment as modification treatment within carbon steel anode limitations. The current study investigates an area that has not been studied previously by any researcher, which is E.O. effect on the shear strength of a Baghdad clayey soil high PI while at soft state, or at uniform condition. In addition, in this study the effects of E.O. application to increase pile installation efficiency (during pile drivage though this ground) will be studied.

2. Method

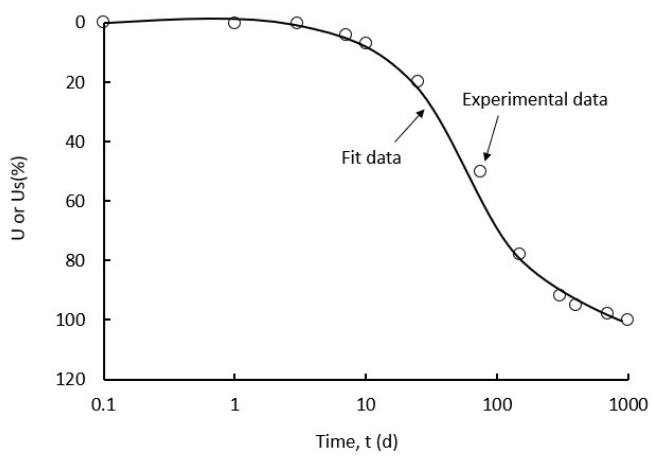
2.1 Methodology and materials

2.2 Clayey soil properties (physical, compaction and permeability)

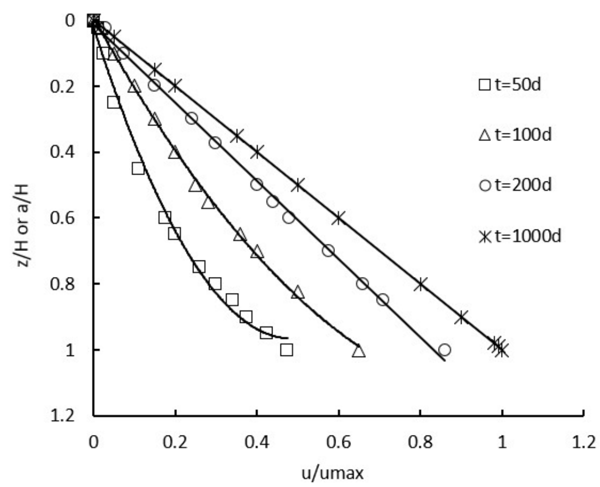
The procedure shown in Fig. 6 is intended to give a general assessment of the role of electro-osmosis in soft clayey soils. With systematic soil characterization and E.O. application under controlled and practical filling conditions, in combination with detailed measurements of the related soil parameters such as shear strength, and the penetration rate of the pile, the study should contribute with useful input for the practice of geotechnical engineering. The organized fashion of results makes them reliable, reproducible, and relevant for practical purposes. The flowchart above outlines the primary tests conducted on light brown soft clay samples, which were extracted from a depth of 2 meters at the Al-Ikhwa residential investment complex. This complex is situated between Abu Ghraib Road and Airport Road in the western regions of Baghdad. The light brown, medium to soft silty clay layer can be classified as a CL soil according to the soil classification system. Table 1 compiles all the collected data regarding the soil and its properties.

Table 1. Properties of silty clay soil.

Test	Parameter	Results	ASTM
Atterberg limits	LL, PL, P.I.	36.13, 18.5, 17.6	D4318-10
Specific gravity	Gs	2.71	D854-14
Passing sieve #200	Fines%	92.5	D1140-14
Hydrometer finer (0.002)	Clay%	40	D7928-17
Compaction	γ_{dry}, ω_{opt}	1.55 gm/cc, 18%	D698-12
Failing head	k	$8.4 \times 10^{-9}(m/s)$	D5856-15
Vane shear V.S. for (25% and 30%)	Cu	$\approx$ 22 and $\approx$ 10 kPa	D2573-15
Soil classification	—	CL	D2487-11



(a) Present analytical



(b) Water pressure distribution

Figure 5. (a) A comparison is made between the present analytical solution and the existing one. (b)The variation of σ in time is shown in, and the excess pore water pressure distribution is shown in, with d referring to days, which is used throughout the following figures and tables (redrawn by author).

2.3 Clayey soil preparation

Once sufficient volume of soil was collected at the project site, samples were oven-dried to constant dry weight. The ground was pulverized to fragments to facilitate subsequent grinding. The soil was powdered to fine powder using an electric mill (capacity: 80 kg/h). The dried, crushed prismatic samples were subjected to the unconfined compression tests (U.C.) and the laboratory vane shear test as well. These tests were carried out at three contents of water (ω) to establish the best proportion of moisture for remodelling the samples of soil in a soft condition or consistency. Figure 7 shows vividly the way in which the soil-water content influences the undrained shear strength in Vane Shear (V.S.) and (U.C.) tests.

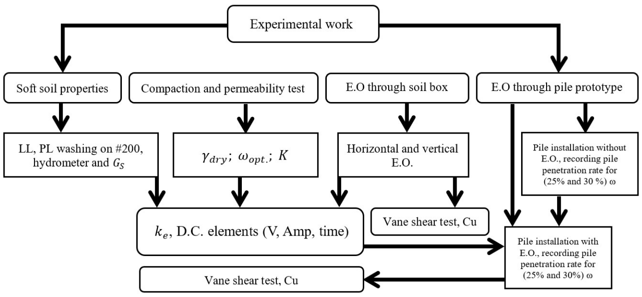


Figure 6. Schematic representation of the research methodology.

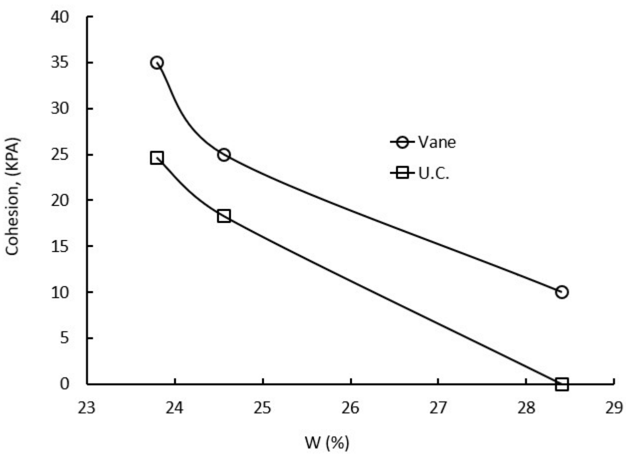


Figure 7. Soil undrained shear strength soil moisture content relation.

2.4 E.O. through clayey soil

In this study, to examine the effects of electro-osmosis (E.O.), soil samples were prepared at a moisture content of 25%. This level was chosen to create a soft consistency in the clayey soil, which was then confirmed using vane shear test measurements. The experiments were primarily carried out using two soil containers. The first container, with dimensions of $42 \times 26 \times 20$ cm, was designed for horizontal E.O. treatment. It incorporated vertically placed direct current (D.C.) electrodes distributed throughout the container, as illustrated in Fig. 8. In the second trial, a vertical electro-osmosis (E.O.) setup was prepared using horizontally positioned stainless steel rectangular electrodes that spanned the entire cross-sectional area of the container. The container, made from Plexiglas, was then connected to explore the effects of vertical E.O. on light brown silty clay soil from Baghdad, as shown in Fig. 9. It is crucial to verify that both horizontal and vertical soil containers are used to test and assess electro-osmosis (E.O.) parameters for Baghdad's soft to very soft silty clay soils. This evaluation is essential for the subsequent soil stabilization phase, which will involve analysing the undrained shear strength of the soil following the completion of the treatment process.

2.5 Using insulated electrical soil containers for verifying pile driving efficiency due to E.O.

In the experimental setup, a pile shaft prototype measuring 3 cm by 3 cm by 30 cm was utilized to simulate the pile driving process. A Plexiglas two-dimensional soil container was employed to predict the pile penetration rate through a layer of soft clayey soil at its normal consistency. This was conducted for both the initial trial and the same soil after the application of electro-osmosis (E.O.) along the length of the pile shaft. The experiments considered two water content levels, specifically 25% and 30%.

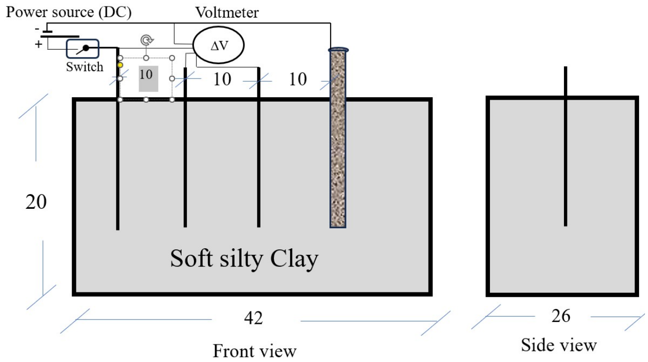


Figure 8. Horizontal E.O. soil container, electrodes, power supply, and other accessories, (All units are in cm).

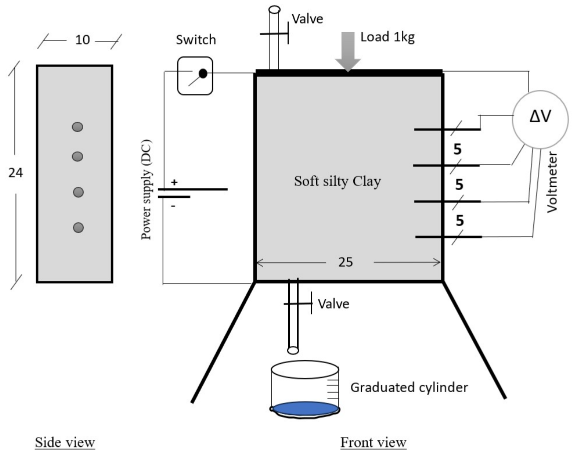


Figure 9. Vertical E.O. soil container, electrodes, power supply, and other accessories, (All units are in cm).

2.6 Samples preparing and test procedures

The experimental work was conducted in two main phases to assess the impact of electro-osmosis (E.O.) on the undrained shear strength of soft silty clayey Baghdad soil with a water content of 25%, using a vane shear (V.S.) apparatus. Additionally, four further trials were carried out on soil with two different water contents (25% and 30%) to measure pile driving efficiency. The trials included two control tests and two tests on soil of the same water content and pile shaft dimensions after E.O. was applied along the pile shaft. The soil was allowed to cure for approximately 24 hours after adding a specific amount of water, then covered with a plastic sheet and a wet cloth. It was compacted in layers to achieve a density of 2 gm/cc, matching the density required for unconfined compression (U.C.) tests. The container was treated with a suitable oil to minimize friction between the soil mass and facilitate easier extrusion of the soil after testing. For the initial test involving the application of D.C. in a horizontal direction with vertical electrodes, it was necessary to electrically insulate the container surfaces. This precaution was taken to prevent them from acting as separate cathodes, which could result in non-uniform electrical intensity and potential loss of volts or electrical energy through the container walls. To ensure a comprehensive understanding of the testing procedure, it is essential to outline the tools, containers, and electrical equipment utilized throughout the entire testing process. These included:

- A D.C. Power supply - Oral when 30 volts at 10 amperes.
- U.P.S. for A.C., 1000 VA "Backup power supply unit during a power failure.
- Urchin Several types of metal rod, such as stainless steel, brass, carbon steel (widely used in construction), and strips of carbon steel and stainless steel, as well as anode and cathode, respectively.

- A pre-rolled stainless steel hollow cylinder with a diameter of 2 in. filled with dry, loose, poorly graded sand for observing E.O.-induced moisture flow toward the cathode in the first test.
- Four-channel digital multi-reader electrical measurement equipment for voltage switch-gradients monitoring.
- Weighing, an oven sample, and a can, precision 0.01 g for water content.
- A vane shear apparatus for measuring unconsolidated undrained strength.
- An optional soil resistivity device.
- A graduated model of a concrete pile shaft described ($3 \times 3 \times 30$ cm).
- A plastic pile guide.
- A suitable hammer and a steel concrete compactor rod for driving the pile shaft.
- Utilization of a digital room thermometer and an electronic humidity sensor for monitoring the ambient conditions of soil samples.

The majority of the instruments mentioned can be identified in Fig. 10. In the first trial, the soil was compacted in horizontal layers across the entire container area, including around a fixed prefabricated vertical cylinder (2 inches in diameter) that would serve as the cathode in the subsequent electro-osmosis (E.O.) process. Once the soil reached the required depth, initial vane shear readings were recorded. Direct current (D.C.) electrodes were then connected to the D.C. power supply to apply various potential differences (voltages), while monitoring the current consumption (amperage).

(a) Power supply

(b) U.P.S.

(c) Multi-reader

(d) Shear device

(e) Prototype

Figure 10**.** (a) D.C. power supply, (b) U.P.S. power supply, (c) Digital multi-reader electrical measurement, (d) Vane shear device, (e) Pile concrete shaft (graduated) prototype.

During this process, voltmeter probes were attached to two intermediate bars to measure the voltage gradient, as shown in Figs. 11, 12, and 13. After the test was completed, final vane shear readings were taken at multiple surface locations (near the anode and cathode). For the vertical E.O. trials and the subsequent pile driving efficiency tests, a Plexiglas electrically insulated box was used, representing a different E.O. cell configuration. The procedure followed for this trial was similar to the first, with three main differences. First, the direct current (D.C.) probes were designed as stainless steel rectangular meshes that covered the entire area of the soil container. Second, electro-osmosis (E.O.) was applied in a vertical direction. By positioning the anode at the top and the cathode at the bottom of the container, moisture movement was facilitated by both gravity and E.O., potentially enhancing the efficiency of the process, Consequently, the final vane shear readings were recorded at the surface near the anode and at specific depths towards the cathode. The last four tests, which focused on pile driving efficiency, used the same mold size as the second trial but did not employ two horizontal rectangular electrodes for E.O. induction. Instead, a stainless-steel strip served as the anode, embedded vertically 10 cm from the soil surface and located 5 cm away from the pile shaft edge. The cathode was represented by a 2.5 cm steel strip, fixed along one of the pile prototype shaft faces using a suitable epoxy resin, as depicted in Fig. 12. The electro-osmosis (E.O.) process is initiated once the compaction of the clayey soil is complete, and the pile guide is installed. The pile shaft is equipped with a cathode attached at a depth of 5 cm and an anode at 10 cm. A direct current (D.C.) is applied for approximately 1.5 to 2 hours, after which the pile driving process commences, continuing until the pile shaft reaches a depth of about 25 cm. For the pile control test, the driving process is carried out without the application of D.C., and vane shear readings are taken before and after the pile driving for all tests.

Figure 11**.** Horizontal E.O. soil container, E.O. electrodes, and voltmeters.

Figure 12**.** Following the completion of the pile driving process with electro-osmosis (E.O.) enhancement, the pile shaft prototype is depicted with the red wire indicating the anode and the black wire representing the cathode.

(a) Electrodes state

(b) Soil solidification

Figure 13**.** (a) Electrodes state due to E.O. subjecting for about (48) hours, (b) Soil solidification mass around the pile prototype shaft due to E.O. subjecting for about (48) hours.

Upon completion of the pile driving, E.O. is sustained for an additional 48 hours to assess its effects on the soil surrounding the pile shaft area. Post-tests, observations were recorded for both the anode and the pile shaft. The anode was carefully removed, and the soil mass was released to examine soil cementation (hardening volume). In both tests, the anode exhibited corrosion of approximately 50% of its original area as in Fig. 13. The soil masses were observed to have solidified in large volumes around the pile body prototype; this solidification is attributed to the migration of positively charged particles, along with metallic corroded constituent parts, towards the cathode zones. It is crucial to note that the moisture content of the soil throughout all testing stages was monitored both directly, by analysing small soil samples, and indirectly, through measuring the soil's resistivity. The resistivity was found to be inversely proportional to the soil's moisture content, although a detailed logarithmic relationship was established and is documented elsewhere, as it falls beyond the scope of this study.

3. Results and discussion

3.1 Results for some of E.O. parameters and their validity

As this study marks the initial attempt to apply electro-osmosis (E.O.) to clayey Baghdad soils, it is essential to conduct foundational or preliminary tests. These tests aim to document key E.O. parameters, including electro-osmotic permeability (ke in m^2/sV), voltage gradient (electric field intensity, E in V/m), drainage due to electro-osmosis (Q_e in ml), and the efficiency factor (β). Figure 14 presents a summary of the collected data, which is instrumental in predicting these parameters for the horizontal E.O. pattern. Consequently, the electro-osmotic flow moves water from the anode to the cathode, resulting in a decrease in water content near the anode (leading to desiccation) and an increase near the cathode.

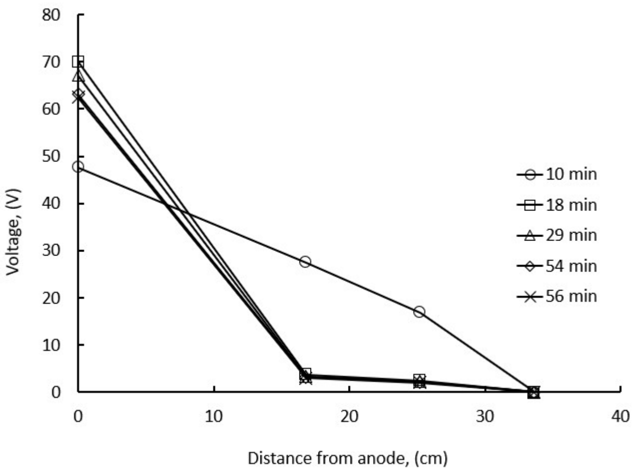


Figure 14**.** Voltage gradient measurements across the horizontal electro-osmosis process at different time intervals.

This reduction in water content near the anode causes an increase in the soil's electrical resistivity, which in turn steepens the voltage gradient in that area. Generally, the nonlinear (nonuniform) voltage gradient characterized by a sharp initial drop near the anode, followed by an irregular decline, is a natural consequence of electrochemical reactions. These reactions include electrode corrosion, pore blockage, and changes in pore water chemistry and water aggregate distribution when using corrodible steel electrodes in the electro-osmosis process. Table 2 presents the horizontal electro-osmosis (E.O.) parameters, which will be compared with the subsequent vertical E.O. results. Table 3 gives the computed vertical E.O. parameters. The outcomes of the tests were initially influenced by both vertical Fig. 15 and horizontal electro-osmosis (E.O.) processes. However, the more logical and plausible results were obtained from the horizontal E.O. approach. This may be attributed to the fact that the soil mass was prepared in horizontal, levelled layers within the container, which aligns with the natural formation of soil as horizontal strata in soil profiles. This conclusion is consistent with numerous soil formation studies, such as those examining the origins and implications of soil layering. These studies have demonstrated that stratification in soils is a common occurrence, resulting from various pedological and geological processes, and it plays a significant role in the interpretation of soil and landscape characteristics [33]. A brief duration was selected for the application, with the intention of using an equivalent timeframe in subsequent pile driving tests. This decision was influenced by the need for rapid pile shaft installation within the soft clayey soil during the driving process.

3.2 Undrained shear strength readings

Observations from all electro-osmosis (E.O.) tests, including horizontal, vertical, and pile driving, were particularly clear in the vertical and horizontal E.O. modes. However, the results were not as distinct for the final pile driving sets. This discrepancy occurred because the distance between the electrodes was only 5 cm, which was closer than in the first two sets of tests. Additionally, this reduced spacing led to a higher degree of corrosion on the anode, as illustrated in Fig. 13a.

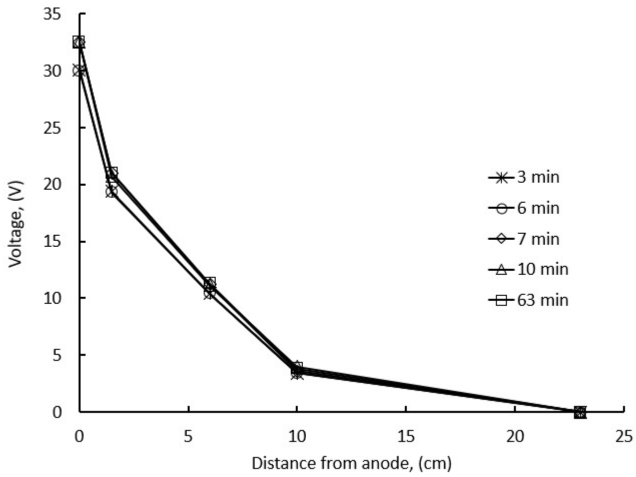


Figure 15**.** Voltage Gradient Assessments Throughout Different Vertical Electro-Osmosis Treatment Phases.

3.3 Horizontal and vertical E.O. soil container

In comparison to the horizontal electro-osmosis (E.O.) setup, the undrained shear strength exhibited more significant changes and distribution in the vertical E.O. configuration. Figures 16 and 17 illustrate the variations at vane shear (V.S.) readings, denoted as cu(kPa), for both horizontal E.O. tests.

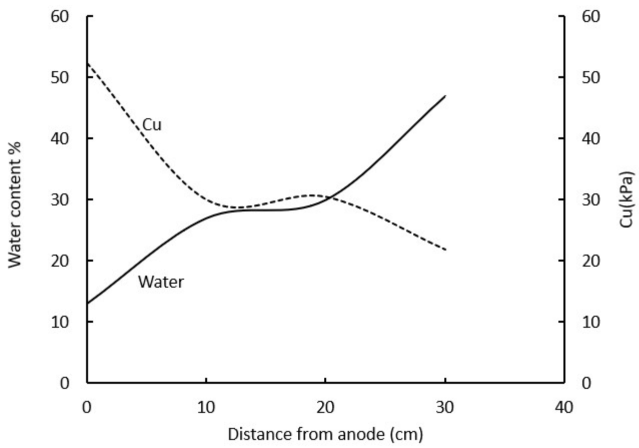


Figure 16**.** Relationship Between Undrained Shear Strength (kPa), Horizontal Distances (cm) from the Anode and soil water content distribution.

The experimental data demonstrate distinct performance trends for vertical and horizontal E_o in silty clay (CL, LL=36.1, PI=17.6). Horizontal EO achieved superior shear strength improvement, with an increase from 22 to 47 kPa near the anode, correlating with reduced water content ($\omega = 13\%$). The spatial variability in Cu Fig. 16 and non-linear voltage decay Fig. 16 highlights the influence of electrode polarization and soil heterogeneity (40% clay). In contrast, vertical E.O. showed weaker but more uniform enhancement, with a value of improvement ranging from 1.4 to 1.8 cu gain Fig. 17 and gradual voltage drop Fig. 15, the post-treatment strength measurements indicate a noticeable enhancement in the Cu; values. However, when compared with the data previously collected by [27], the improvement appears to be relatively modest, attributed to gravity-assisted drainage. The low efficiency factor, $\beta = 22.3\%$, Table 2, underscores the need for optimized cathode materials (e.g., stainless steel over carbon steel). Both methods confirm E.O.'s effectiveness in low-permeability soils ($k = 8.4 \times 10^{-9}$ (m/s)), with horizontal E_o preferred for surface stabilization and vertical E_o for deeper treatment. For field applications, pulsed DC and moisture control ($\omega \approx 18 \rightarrow 25\%$) are recommended to balance performance and energy costs. These findings align with the results reported by [8], which demonstrated that the E.O. technique can effectively strengthen and consolidate the gray clay of Tabriz.

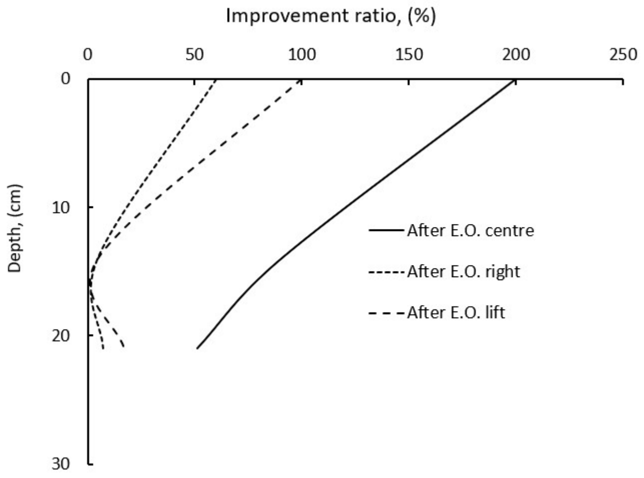


Figure 17. Correlation Between Undrained Shear Strength (kPa) improvement ratio and vertical depth (cm) from the Anode, vertical E.O.

3.4 Pile prototype installation using E.O. stabilization method

As previously stated, the experimental program was designed to identify the optimal electro-osmosis (E.O.) parameters that would facilitate the most efficient pile prototype installation within the local light brown soft silty clay layers found in Baghdad. Figures 18 and 19 illustrate the cumulative number of blows required for pile penetration at different depths within the pile shaft, measured in centimetres. These figures correspond to soil moisture levels of 25% and 30%, respectively, and compare the results from conventional pile driving methods with those enhanced by electro-osmosis (E.O.). Figure 12 depicts the final stage of soil pile installation under electro-osmosis (E.O.) conditions, highlighting the positions of the anode and cathode. It is evident from the figure that metallic cementation ions migrate from the anode towards the cathode, a phenomenon clearly represented by the brown colour. Following the above observations leads to excluding the object of testing the hardened soil beyond the E.O. electrodes. This selection was based on an undrained soil shear strength test in a container at the dry density of 20 kPa at soil moisture content of 25% and 10 kPa vane shear test before E.O. subjecting. Nevertheless, as E.O. process reached its end convert the soil to solid state for certain parts, it was discovered that the newly generated soil shear strength was higher than the vane shear tool scale; This outcome signifies that electro-osmosis (E.O.) treatment has substantially enhanced the overall pile capacity compared to traditional pile installation techniques, a finding supported by numerous previous studies [29, 30, 33, 34] which clearly demonstrate improvements in pile capacity across various ratios. For conduct comparison among stabilized and normal tests, it is necessary to compute P.R.B. as in Eq. 1.

$$P.R.B = \frac{Cumulitave\ B\ without\ E.O. - Cumulative\ B\ with\ E.O.}{Cumulitave\ B\ without\ E.O.} \quad (1)$$

Table 2. Horizontal E.O. parameters.

Parameter symbol	Unit	Value	Typical values	Validation (range)
k_e	$m^2/s.V$	2.4×10^{-9}	$(1 \rightarrow 5) \times 10^{-9}$ [35]	∘ Result within typical range for silty clay soils.
β	——	22.3%	$27 \rightarrow 68$ % [14]	∘ Result out of range due to using normal carbon steel bars
E_o	V/m	142	∘ Low to Moderate Gradients $10 \rightarrow 50$ ∘ Higher Gradients: Up to $\rightarrow 100$	∘ Huge number due to short inducing D.C. period. ∘ It is important to consider that the true voltage gradient in the soil can be different because the soil is non-homogeneous there are also electrode reactions (as in previous answers) and changes in the chemistry inside the pore fluid. The above values correspond to mean gradient applied.
E_e	V/m	142		

Table 3. Horizontal E.O. parameters.

Parameter symbol	Unit	Value	Typical values	Validation (range)
k_e	$m^2/s.V$	1.95×10^{-9}	$(1 \rightarrow 5) \times 10^{-9}$ [35]	∘ Result within typical range for silty clay soils.
β	——	52.4%	$27 \rightarrow 68\%$ [14]	∘ The results are consistent as we would expect, since stainless steel metal is placed along the entire cross section of the vessel.
E_o	V/m	99	∘ Low to Moderate Gradients $10 \rightarrow 50$ Low to mid. ∘ Higher Gradients: Up to $\rightarrow 100$ Higher [36]	∘ Huge number due to short inducing D.C. period. ∘ It is important to consider that the true voltage gradient in the soil can be different because the soil is non-homogeneous there are also electrode reactions (as in previous answers) and changes in the chemistry inside the pore fluid. The above values correspond to mean gradient applied.

Upon reviewing the pile resistance behaviour (P.R.B.) results, it is evident that utilizing soil with a water content of 25% yielded a distinct and beneficial impact on the efficiency of pile installation through E.O. within range (65-88%). This positive effect was not observed when the soil had a higher water content of 30%, as depicted in Figs. 18 and 19. This discrepancy could be attributed to several factors, indicating that more blows were sometimes required with E.O. compared to without E.O. at certain depths. This could suggest that for this higher initial moisture content, the E.O. effect on reducing penetration resistance might not be as pronounced, or perhaps the E.O. parameters were not optimal for this soil condition/installation method. Further analysis would be needed to understand why the benefit is not consistently observed. After examining the relationships, it's clear that the curves collectively show an increased pile penetration rate for prototypes that have been stabilized using electro-osmosis (E.O.). However, this enhancement is not consistent throughout the entire pile body. Specifically, areas near the pile head show a reduced penetration rate, likely due to the remolding effect on the soft clay layer surrounding the sides of the pile at water contents exceeding 25%, as illustrated in Fig. 20. This effect might also result from rapid pile installation in soils with higher moisture content, which leaves insufficient time for E.O. to promote free water movement and ion exchange.

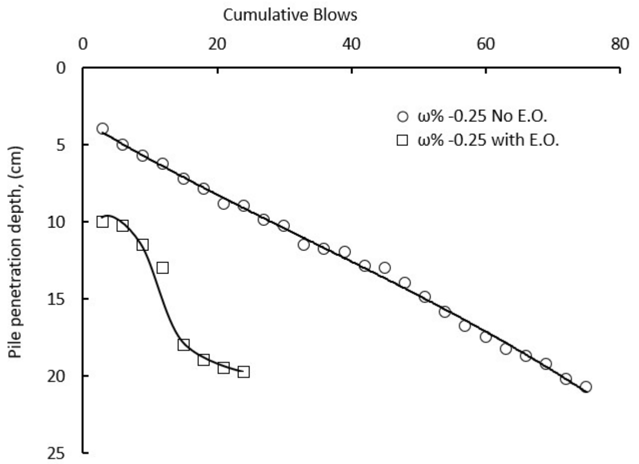


Figure 18**.** Correlation between pile cumulative blows and pile depth (cm) at a soil moisture content of 25%.

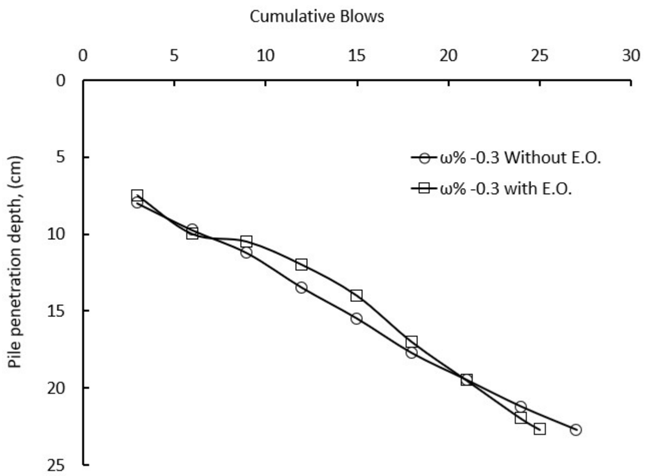


Figure 19**.** Relationship between pile cumulative blows and pile depth (cm) at a soil moisture content of 30%.

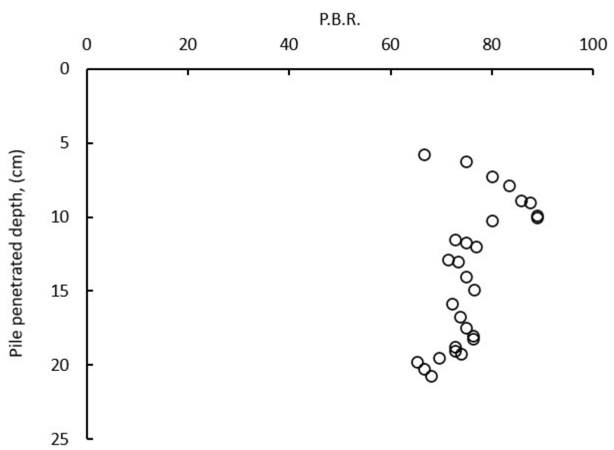


Figure 20**.** Relationship between P.B.R and pile depth (cm) at a soil moisture content of w=25%.

It is logical to deduce that a higher penetration rate for the pile shaft will lead to decreased labor requirements for pile installation, meaning less time will be spent driving the pile. This, in turn, will significantly reduce the time needed to complete this phase of the project. Nikolaev (1962) documented similar findings, noting that driving wooden piles with E.O. assistance requires fewer hammer blows and results in a faster and more efficient penetration rate compared to traditional methods [15]. Consequently, this technique also minimizes deformation at the tops of the piles.

4. Conclusion

This study, bolstered by empirical data, investigates electro-osmosis (E.O.) stabilization influences the undrained shear strength of light brown clayey soils under the influence of both vertical and horizontal direct current (D.C.) conditions. The objective of the research is to assess the viability of employing E.O. in geotechnical engineering, particularly within the context of pile driving operations. Overall, the findings allow us to conclude that:

- Soil Characterization The soil was characterized using standard geotechnical tests, indicating a silty clay (CL) with high fine content (G = 2.71). These characteristics are fundamental to comprehend the soil behaviour subjected to E.O.
- Electro-Osmosis (E.O.) Parameters: Key parameters of E.O., such as k_e, β, E_o, and E_e were determined as important for the process optimization. The deduced values are in or near the standard ranges given in the literature, and hence demonstrate the solidity of the experiment method.
- The results from vane shear tests indicated that the undrained shear strength of clays was significantly enhanced by E.O. treatment, particularly at the 25% moisture content. Different consolidation rates were observed in different depths.
- Pile Penetration Efficiency: The pile penetration rates increased significantly with E.O. treatment, especially at 25% MC. The results from Figs. 7 and 8 indicate that E.O. has an effect on the number of blows for pile installation, which can improve efficiency.
- Voltage Gradient and Soil Moisture The voltage gradients diminished with distance from the anode Figs. 4 and 5. The responses of voltage to these three variables were complicated and E.O. resulted in greater effects for drier moisture contents.
- The experimental data clearly demonstrates that horizontal E.O. effectively induces a voltage gradient within the silty clay confined in the metallic box. This voltage gradient, which is critical for electro-osmotic consolidation, varies with distance from the anode and treatment duration. The calculated electro-osmotic coefficient, $k_e = 2.4 \times 10^{-5}$ $(m^2/s.V)$, falls within the typical range for silty clay soils ($1 \rightarrow 5 \times 10^{-5}$ $(m^2/s.V)$ as per Mitchell et al., 2025). This validates the fundamental electro-osmotic process and its potential to induce water flow within the soil, thereby influencing its moisture content and shear strength. The observed variation in water content with distance from the anode further supports the occurrence of electro-osmotic dewatering, indicating that the setup successfully facilitated the movement of pore fluid, which is a prerequisite for soil improvement via this method. The present study has been proving confident for utilizing the electro-osmotic for increased efficiency of pile installation in the soft clayey soil of Baghdad. The application of E.O. seems to be a promising method for incrementing the Cu and enhancing the pile driving in 25% and 30% water content conditions.
- Spatial Variation of Improvement and Influence of Moisture Content on E.O. Efficacy: Although the E.O. applied is effective in a vertical plane, the amount of improvement in shear strength is not consistent through the entire soil mass; in fact, it varies spatially. The absolute improvement ratios are largest near the anode, while in general, a reduced efficiency with distance from the anode or depth is noted. This non-uniformity underscores the difficulty with achieving uniform treatment throughout a soil volume with E.O. Furthermore, the overall effectiveness of E.O. (i.e., both vertical and horizontal applications) also seems to be very sensitive of the initial moisture content of the silty clay material, as higher initial moisture content such as 30% results in much less consistent or even negative effects on the pile installation efficiency as compared to the lower moisture content (e.g., 25%). This would indicate that in real use, O.E. condition must be adapted to the specific soil conditions, especially the in-situ moisture regime, to achieve predictable results and advantages.

- It is concluded that electro-osmosis is promising in increasing the undrained shear strength of Baghdad soft clay and in accelerating the installation of piles. In the future, optimal parameters of E.O. for various soils and moisture contents remain topics in scope of new studies, as well as long-term effects of E.O. on soil stabilization.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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