

# Extendable electrode electroosmosis in soft soils: investigating the influence of branching horizontal electrodes

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**ABSTRACT:** Electroosmosis in soft soils often encounters challenges such as uneven reinforcement and increased resistance at later stages, resulting in high energy consumption. To improve treatment efficiency and reduce energy use, an Extendable Electrode Electroosmosis method (EEEEO) is proposed. A distinguishing feature of the proposed method is the use of branching horizontal electrodes formed via air-pressure fracturing, which differs from traditional electroosmosis. This study conducted laboratory experiments to evaluate branching electrodes of different lengths—full, one-third, and one-quarter—and compared their drainage performance with that of traditional vertical electrodes. Current and voltage were monitored to calculate energy consumption. In addition, a multi-physics simulation using COMSOL was performed to analyze the electric field distribution within the new system. Experimental and simulation results show that electrodes with one-quarter fracturing length achieve both the highest drainage performance and the lowest energy consumption. Among the branching horizontal electrode tested, fully penetrating electrodes result in higher total current. However, much of the current bypasses the soil, leading to limited improvement in drainage efficiency. In contrast, the one-quarter length group ensures that the electric field is more effectively distributed within the soil, generating stronger potential gradients that enhance water migration. Moreover, the horizontal electrodes themselves function as drainage channels, increasing the effective permeability of the soil. These results provide engineering guidance for optimizing electrode parameters in electroosmosis applications and support the development of more efficient, scalable, and sustainable ground improvement solutions.

**KEYWORDS:** Extendable Electrode Electro-osmosis, Soft Soil, Ground improvement, Branching Horizontal Electrodes, Electric Field Distribution, Drainage Efficiency.

## 1 INTRODUCTION

Electroosmosis is a ground improvement technique that enhances soil drainage and consolidation by applying direct current to electrodes embedded in the soil (Sun et al., 2024). Its dewatering performance is not constrained by low hydraulic conductivity, enabling efficient drainage even in fine-grained soils with high water content and poor permeability (Zhou et al., 2023). These characteristics make it especially suitable for soft clay ground improvement. However, despite its theoretical advantages and decades of research, large-scale field applications remain limited due to high energy consumption.

Laboratory investigations have revealed that the primary cause of high energy consumption in electroosmosis lies in the progressive increase of interfacial resistance between the electrodes and the surrounding soil (Guo and Zhuang, 2022). As the process continues, excessive drainage near the anode often leads to localized desiccation, resulting in a sharp rise in interfacial resistivity and contact resistance. These factors collectively reduce the effective voltage applied across the soil, weakening the electric field and diminishing electroosmotic flow (Sha et al., 2021). Moreover, the elevated interfacial resistance intensifies Joule heating, converting a substantial portion of electrical energy into heat rather than contributing to drainage. As a result, a significant amount of energy is lost through thermal dissipation. Overall, the high energy demand of electroosmosis is primarily driven by (1) prolonged operation during low-efficiency stages and (2) the continuous growth of interfacial resistance, which severely limits energy utilization efficiency.

To address the limitations of conventional electroosmosis, an Extendable Electrode Electroosmosis (EEEEO) method is proposed. As illustrated in Fig. 1, the EEEO approach integrates air-pressure fracturing (Venkatraman et al., 1998) with the injection of conductive modifiers to form extendable horizontal electrodes within the soil. These fractures act not

only as conductive paths but also as horizontal drainage channels.

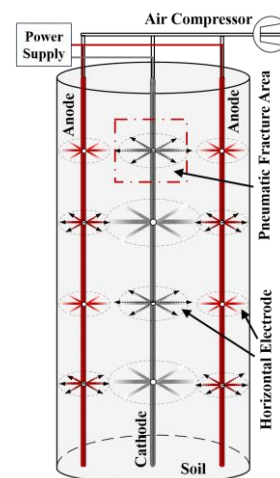


Figure 1. Schematic Diagram of EEEO.

Compared to traditional electroosmosis, where electrodes remain fixed and spacing vertical, the EEEO method enables electrodes to grow progressively, reducing the spacing between anodes and cathodes over time. This dynamic configuration could enhance the electric field strength and accelerate drainage. Therefore, understanding the mechanism by which horizontal electrodes influence electroosmotic performance is essential to the development and application of this technique. However, existing studies on horizontal electrodes in electroosmosis are limited and primarily focus on parallel horizontal arrangements (Bian et al., 2024), typically positioned above and below the soil layer. In contrast, the EEEO method introduces horizontal electrodes branching out from vertical electrodes.

This study investigates the effects of horizontal electrodes on electroosmotic drainage efficiency and energy consumption, and further explores the underlying mechanism through the analysis of electric field distribution and potential gradients. Laboratory experiments are conducted to compare different electrode length, and numerical simulations based on COMSOL Multiphysics are used to analyze the resulting electric field distribution. The combined results help clarify the mechanism by which horizontal electrodes enhance electroosmotic drainage.

## 2 LABORATORY ELECTROOSMOSIS EXPERIMENTS

### 2.1 Materials and methods

To investigate the influence of horizontal electrodes, a series of laboratory experiments was conducted. A horizontal conductive layer composed of graphite was pre-embedded in the soil. The electro-osmotic consolidation apparatus is shown in Figure 2. The device consists of a model box, power supply, voltmeter, ammeter, and a drainage collection unit that records the volume of water discharged from the cathode. The model box measures 200 mm × 100 mm × 120 mm (length × width × height). Potential probes were installed at 65 mm and 130 mm from the anode to monitor potential changes in the anode zone (0–65 mm) and the central zone (65–130 mm). A horizontal electrode layer with a thickness of approximately 10 mm was embedded at the mid-height of the soil sample (55 mm above the base). The horizontal electrodes were composed of 300-mesh high-purity graphite powder, with a conductivity of 20 S/m in the loosely packed state—approximately 80 times higher than that of the clay used in the experiment.

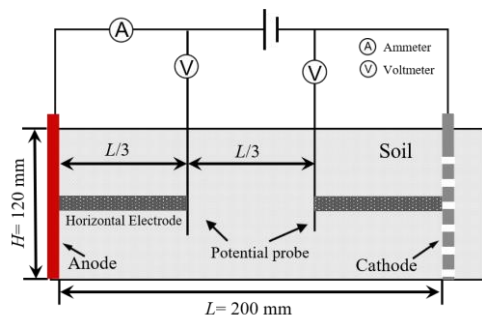


Figure 2. Schematic of the experimental apparatus.

All electroosmosis tests applied 20 V constant DC potential for 24 hours by which time drainage had stopped. Four experimental groups were designed with symmetric horizontal electrode lengths as the variable: (1) One-half length (fully penetrating), (2) One-third length, (3) One-quarter length, and (4) No horizontal electrodes (control group).

The test soil, a typical low-permeability Hangzhou clay (Fu et al., 2025), was obtained from a pit in the western part of Hangzhou. Its physical properties were as follows: water content  $w=58.5\%$ , specific gravity  $G_s=2.75$ , void ratio  $e=1.47$ , liquid limit  $w_L=45.3\%$ , plastic limit  $w_P=23.5\%$ , and electrical conductivity  $\sigma_e=0.25$  S/m. To ensure the homogeneity of the specimens, remolded clay was prepared. The in-situ soil was first dried and ground into fine powder, after which deionized water was added to achieve a target water content of 80%. The mixture was then sealed and left to stand for over 72 hours before testing.

The working electrode was an EKG (Electro-Kinetic Geosynthetics) plate electrode, measuring 5 mm × 100 mm × 140 mm. The cathode plate was perforated to allow pore water to pass through. The portion of the EKG electrode in direct contact with the soil was primarily composed of non-metallic

graphite material. During the test, oxygen evolution occurred on the anode surface. Polished copper rods were used as potential probes to monitor voltage distribution within the soil.

### 2.2 Results and analysis

#### 2.2.1 Electroosmotic Efficiency

Figure 3 presents the drainage and energy consumption results obtained from the electroosmosis tests. As a commonly used index in electroosmosis studies, drainage volume serves as a key indicator for evaluating the effectiveness of soil improvement. Total energy consumption was calculated based on the recorded current and the applied voltage. The energy consumption coefficient, defined as the ratio of total energy input to cumulative drainage volume, reflects the efficiency of energy utilization—lower values correspond to higher energy efficiency.

With the inclusion of horizontal electrodes, all test groups exhibited higher drainage volumes compared to the conventional electroosmosis group. However, a longer horizontal electrode did not necessarily result in better performance. Under the conditions of this study, the group with a one-quarter-length layer achieved the best drainage outcome, while the one-third and one-half groups showed similar drainage volumes. Energy analysis revealed substantially higher total energy consumption and elevated energy consumption coefficients in the fully penetrating (half-length) electrode, contradicting energy-saving objectives. The one-quarter graphite layer demonstrated both the highest drainage efficiency and the lowest energy consumption coefficient, with a 22.8% increase in drainage volume and a 17.7% reduction in energy consumption coefficient compared to the control group.

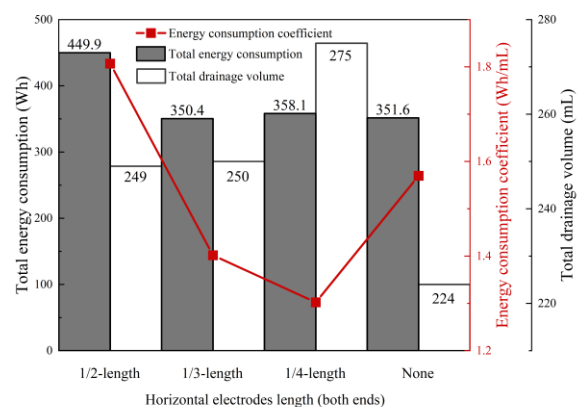


Figure 3. Total drainage and energy consumption

#### 2.2.2 Current and Resistance Variation

Further analysis of current and soil resistance variations helps elucidate how horizontal electrodes enhance drainage. The inclusion of horizontal electrode led to a significant increase in current (Fig. 4). During the initial stage of electroosmosis, longer horizontal electrodes exhibited higher currents, which then gradually declined as drainage progressed. After approximately 10 hours of electrification, the currents in the one-third and one-quarter length groups dropped below that of the control group, primarily due to increased soil resistance resulting from effective water removal. By the end of the test, the descending order of current magnitude was: half-length > control > one-third length > one-quarter length. Notably, the half-length group sustained significantly higher current levels throughout the test period, with the final current nearly double that of the control group.

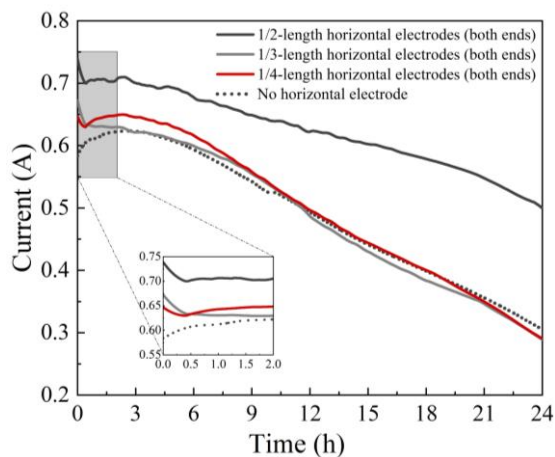


Figure 4. Change of current with time.

The soil resistance in different zones was monitored throughout the tests. Resistance was calculated by dividing the potential drop across each zone by the corresponding current, and the results are shown in Figure 5. The anode zone refers to the region extending from the anode to a horizontal distance of 65 mm, while the central zone covers the range from 65 mm to 130 mm from the anode. In the half-length group, both the anode zone and the central zone were affected by the presence of horizontal electrodes. In contrast, the central zones of the one-third and one-quarter length groups consisted entirely of unmodified soil, while their anode zones included the horizontal graphite electrodes.

The variation in soil resistance within the central zone revealed distinct differences among the test groups. The half-length group exhibited significantly lower resistance compared to the other three groups, due to the enhanced bulk conductivity provided by the continuous graphite electrode. The remaining groups—control, one-third, and one-quarter length—shared similar initial resistance values, which gradually increased as drainage progressed. This increase in resistance was directly correlated with drainage volume. By the end of the test, the one-quarter-length group, which achieved the highest cumulative drainage, also showed the most substantial rise in central zone resistance. The anode zone resistance consists of two primary components: the anode–soil interfacial resistance and the resistance of the soil within the region. As a result, initial resistance values in this zone are consistently higher than those in the central zone. Compared to the control group, all groups equipped with horizontal electrodes exhibited reduced anode zone resistance, with greater reductions observed for longer electrode lengths. The one-third and half-length groups demonstrated similar initial resistance values, as both groups included horizontally distributed electrodes spanning the entire anode region.

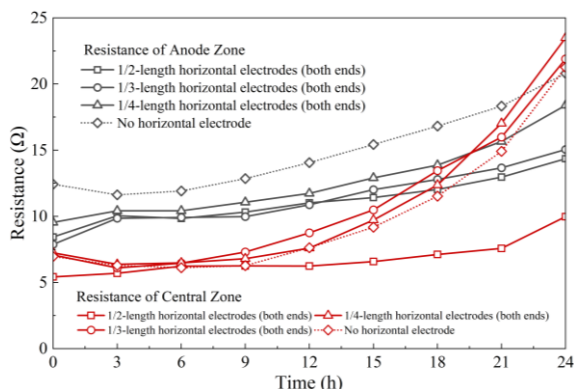


Figure 5. Change of resistance with time

An integrated analysis of current and resistance measurements helps explain why the half-length electrode exhibited significantly higher current yet inferior drainage performance compared to the one-quarter-length group. The elevated current is primarily attributed to the formation of a parallel circuit between the continuous graphite layer and the surrounding soil, which substantially reduced the overall system resistance. However, the effective current passing through the soil did not show a marked increase. As a result, the current enhancement under continuous electrode conditions contributed little to improving electroosmotic drainage efficiency, as reflected by a 9.45% reduction in drainage volume relative to the one-quarter-length.

The presence of horizontal electrodes mitigated efficiency losses associated with localized high-resistance zones in the soil, contributing to improved drainage rate. Moreover, horizontal electrodes effectively suppressed the rapid growth of interfacial resistance at the anode. While conventional electrodes are susceptible to concentration polarization and passivation at the electrode–clay interface, horizontal electrodes enhance interfacial electrochemical reaction efficiency, promote energy conversion, and significantly slow the rate of interfacial resistance development.

The laboratory experiments demonstrated the significant influence of horizontal electrode groups on electro-osmotic performance, which also explains the effectiveness of the EEEO. The inclusion of horizontal electrodes effectively enhanced drainage capacity and reduced energy consumption compared to the conventional setup. Among the four groups tested, the one-quarter-length horizontal electrode achieved the highest drainage volume and the lowest energy consumption coefficient, highlighting an optimal balance between energy efficiency and dewatering effectiveness.

While the laboratory results clearly demonstrated the advantages of incorporating horizontal electrodes, the internal electric field distribution remains a key factor in understanding the performance differences. Therefore, a multi-physics numerical simulation was conducted to analyze the influence of horizontal electrode length on electric field development within the soil.

### 3 NUMERICAL ANALYSIS OF ELECTRIC FIELD DISTRIBUTION

#### 3.1 Simulation Methodology and validation

Utilizing COMSOL Multiphysics, this study conducted numerical simulations of the Extendable Electrode Electroosmosis (EEEO) method. Through the integrated use of the Secondary Current Distribution, Solid Mechanics, and Darcy’s Law modules, the simulations examined how the addition of horizontal electrodes influences electric field distribution and current density.

A representative electrode pair from field-scale electroosmotic consolidation in soft clay was abstracted into a two-dimensional model. Details of the boundary conditions, meshing strategy, and horizontal electrode are provided in Figure 6. The horizontal electrodes were modeled as 0.2 m-thick rectangular domains with 0.05 m-radius filleted corners. Localized mesh refinement was applied at the top of horizontal electrode regions to ensure computational stability and convergence. Their functional behavior was simulated by assigning enhanced electrical conductivity and hydraulic permeability to the electrode domains.

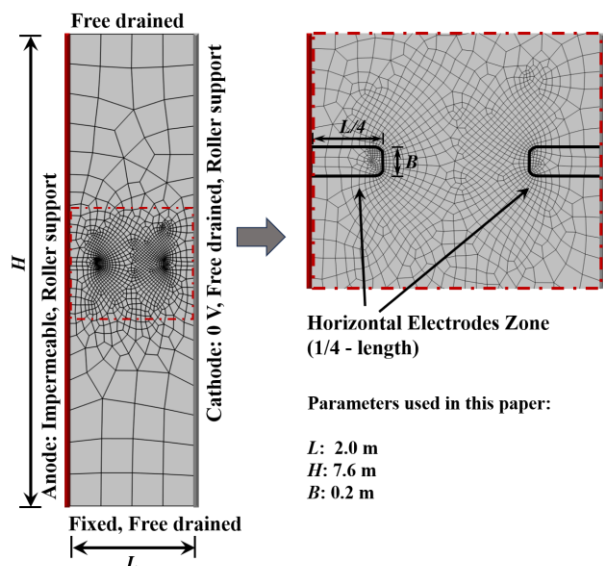


Figure 6. Model mesh and boundary conditions

The Secondary Current Distribution module was used to calculate both electrode polarization and electric potential distribution within the soil. Electrode polarization was modeled using the Tafel equation, expressed as  $\eta = a + b \log i$ , where  $\eta$  is the overpotential and  $i$  is the local current density. The parameter  $a$  represents the equilibrium potential offset, and  $b$  is the Tafel slope reflecting electrochemical reaction kinetics at the electrode–soil interface. Both parameters were selected based on typical values for graphite–clay systems reported in prior studies (Gan et al., 2024), and they reflect the influence of interfacial resistance on potential distribution. The overpotentials of the anode and cathode were determined separately. The total voltage drop due to interfacial overpotentials was subtracted from the externally applied voltage, yielding the effective potential difference actually acting across the soil. Within the soil, the electric field  $\mathbf{E}$  was computed based on  $\mathbf{E} = -\nabla\phi$ , where  $\phi$  is the local electric potential, and the current density  $\mathbf{J}$  followed Ohm’s law:  $\mathbf{J} = \sigma\mathbf{E}$  with  $\sigma$  denoting the soil electrical conductivity. To ensure accurate simulation of steady-state current flow, the model satisfied the current continuity condition:  $\nabla \cdot \mathbf{J} = 0$ . This constraint was enforced throughout the soil and electrode regions, enabling consistent electric field propagation and realistic modeling of electrode–soil interactions. To reflect changes in void ratio during electroosmotic consolidation, electrical conductivity was defined as a nonlinear function of void ratio (Wu, 2009). This approach captures the dynamic evolution of current pathways as consolidation progresses, and is essential for accurately simulating current density distribution.

The Solid Mechanics module was based on Biot’s consolidation theory to simulate the coupled interaction between pore fluid flow and soil deformation. The framework incorporates the momentum balance equation and fluid mass conservation, accounting for both mechanical and hydraulic responses under loading. To reflect the stress-dependency of soil compressibility, the model employs the Duncan–Chang hyperbolic model to capture nonlinear stress–strain behavior (Gan et al., 2022). The Darcy’s Law module was employed to simulate both hydraulic seepage and electroosmotic flow. During electroosmosis, the total pore water flow was considered as a combination of pressure-driven and electric driven movement. To capture the influence of soil consolidation

on fluid transport, both the hydraulic and electroosmotic permeability coefficients were defined as nonlinear functions of the void ratio (Wu et al., 2017). This multi-physics framework enables comprehensive simulation of the electrokinetic response of soil under evolving electrode groups and mechanical states. The main model parameters and their values are summarized in Table 1.

Table 1. Model Parameters Used in Simulation.

Parameter	Value
Initial Young’s modulus, kPa	200
Poisson’s ratio	0.3
Initial hydraulic permeability, m/s	$2 \times 10^{-9}$
Initial electro-osmotic permeability, $\text{m}^2/(\text{V}\cdot\text{s})$	$1 \times 10^{-8}$
Compressibility index	0.25
Initial void ratio	1.47
Soil density, $\text{kg}/\text{m}^3$	1650
Ultimate Deviatoric Stress, kPa	20
Soil electrical conductivity, S/m	0.25
Horizontal electrode electrical conductivity, S/m	20
Horizontal electrode hydraulic permeability, m/s	$1 \times 10^{-6}$
Cathode overpotential constants (a, b)	0.852, 0.217
Anode overpotential constants (a, b)	0.912, -0.12
Cathode equilibrium potential, V	-0.16
Anode equilibrium potential, V	0.1
Applied Voltage, V	36

Although this simulation is not directly tied to a specific engineering project, all parameters were carefully selected to reflect realistic field conditions. The geometric dimensions, applied voltage, and soil properties were determined based on a field-scale electroosmotic consolidation test reported in Gan (2022), while the electrode and material parameters were derived from laboratory investigations. The aim of this simulation is not to replicate a particular project but to capture the essential trends of electric field distribution induced by horizontal electrodes.

Figure 7 presents the simulated cumulative drainage volume over time. The inset figure shows a comparison between the experimental and numerical results after normalization, where the drainage volume of each group is expressed as a percentage relative to the control group without horizontal electrodes. The simulation results exhibit good agreement with the experimental data.

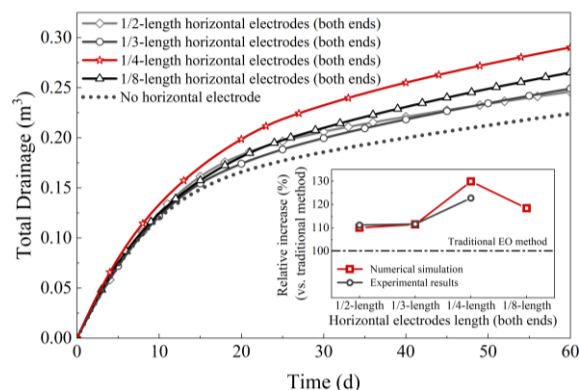


Figure 7. Effect of electrode length on electroosmotic drainage

A parametric analysis of horizontal electrode length reveals that longer electrodes do not necessarily lead to improved

performance, which is consistent with the laboratory findings. This outcome further validates the accuracy and applicability of the proposed numerical method for simulating the Extendable Electrode Electroosmosis (EEEE) process. As shown in Figure 7, the maximum drainage volume was obtained when the horizontal electrode length was one-quarter of the total soil width, confirming that this condition produced the most effective electroosmotic response. In contrast, full-length electrodes did not result in optimal performance. Simulated settlement results also support this conclusion, showing the greatest deformation under the one-quarter length, which enhances soil consolidation and drainage.

### 3.2 Electric Field Distribution Analysis

Figure 8 illustrates the distribution of equipotential lines within a  $\pm 0.9$  m vertical range around the horizontal electrode centerline. Two groups are compared: the most effective one-quarter-length horizontal electrode group (red contour lines) and the control group without horizontal electrodes (gray dashed lines). The shaded rectangles is the schematic location of the one-quarter-length electrodes.

In the control group, the equipotential lines are evenly spaced and nearly parallel across the soil mass, showing a uniform electric field. In contrast, the one-quarter-length exhibits a pronounced densification of equipotential lines in the central soil zone, particularly within 0.3 m above the horizontal electrode layer. The line spacing in this region decreases from approximately 0.2 m (in the control) to as narrow as 0.05–0.07 m, indicating a 3–4 times increase in local electric potential gradient. Since the electroosmotic driving force is directly proportional to the potential gradient, this localized enhancement substantially improves pore water migration efficiency. The results demonstrate that the addition of horizontal electrodes concentrates the electric field in targeted regions, reinforcing the drainage-driving mechanism and confirming the electrokinetic enhancement effect.

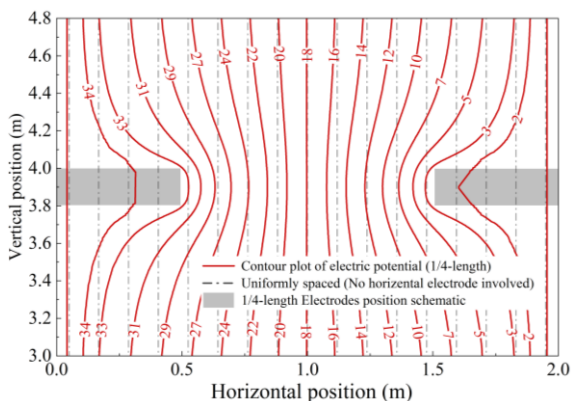


Figure 8. Electric potential distribution under 1/4-length electrodes

Figure 9 illustrates the current density distribution with a fully penetrating horizontal electrode, expressed as a percentage relative to the maximum current density. A distinct, high-density conduction zone—exceeding 80%—is concentrated strictly along the horizontal graphite layer. This shows that most of the current is confined within the highly conductive electrode path, bypassing the surrounding soil mass.

While this group effectively reduces the overall system resistance and generates a higher total current, it does so at the expense of current penetration into the bulk soil. Electroosmosis relies on electric potential gradients across the soil matrix to drive pore water migration. However, when the current is largely short-circuited through the electrode itself, the resulting electric field within the soil becomes weak.

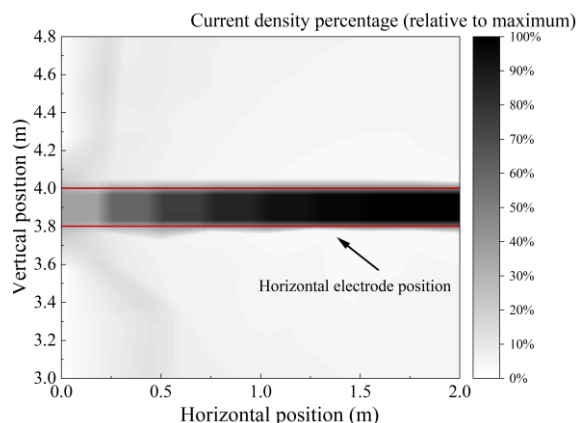


Figure 9. Current density distribution with full-length horizontal electrodes

This observation underscores a critical insight for optimizing the EEEO method: longer horizontal electrodes do not necessarily yield better performance. Instead, partial-length electrodes—such as the one-quarter length—strike a more effective balance by enhancing the electric field within the soil while avoiding excessive current shunting. The findings support the design principle of progressive, extendable electrodes that improve field strength distribution without sacrificing energy efficiency.

## 4 CONCLUSION

This study proposed and evaluated the Extendable Electrode Electroosmosis (EEEE) method as an effective enhancement to conventional electroosmosis techniques for soft soils. By incorporating horizontally extendable graphite electrodes formed via air-pressure fracturing, the EEEO system demonstrated superior electroosmotic performance in terms of both drainage capacity and energy efficiency.

Laboratory experiments showed that the addition of horizontal electrodes significantly increased cumulative drainage and reduced energy consumption. Among the tested groups, the one-quarter-length electrode achieved the best overall performance, with both the highest cumulative drainage and the lowest energy consumption coefficient. In contrast, the full-length electrode group, despite increasing the total current, exhibited reduced electroosmotic efficiency, as a large portion of the current bypassed the soil matrix through the highly conductive graphite layer rather than contributing to pore water migration. Current and resistance measurements revealed that the enhanced performance is primarily attributed to improved current and the mitigation of interfacial resistance buildup. Mechanistically, the introduction of horizontal electrodes reshaped the internal electric field distribution within the soil.

Multi-physics numerical simulations using COMSOL Multiphysics further confirmed these findings. Simulated electric field and current density distributions aligned closely with experimental results and demonstrated that longer electrodes did not necessarily improve performance. The one-quarter length produced the most favorable electric field gradient and deformation pattern, confirming its superiority.

Overall, the combined experimental and numerical evidence validates the effectiveness of the EEEO method. These findings not only elucidate the underlying mechanism of horizontal electrodes in the EEEO system and provide a basis for optimizing their length design, but also offer transferable insights that can be applied to other scenarios involving multi-layer horizontal electrode configurations, such as indoor sludge dewatering, thereby supporting broader electroosmotic design practices.

## 5 ACKNOWLEDGEMENTS

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