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Influence of Voltage on Pore Water Pressure for Soft Soil Treated with Electro-Osmosis Technique

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ABSTRACT

Geotechnical engineers have a difficult time working with soft soils because they require a long time to reach their final settlement and drain water under pressure. Granular columns and other modern technology are only two of the many methods utilised to hasten this levelling. In this study, the alteration of clay soils with a granular column and the evacuation of water by an electric field were replicated using 2D engineering and a finite component. Solid mechanics and electrical interfaces were built using the drag interface. Mohr–Coulomb theory relies on a granular column and fine clay soil at the mechanical contact and employs electro-osmosis to describe a model's electric field's impact. For a period of 6 months, the pore water pressure for fine clay soil was calculated. Result showed that when the electric current was applied with a voltage of 5 V, the pwp in soil increased in the first 2 months and then began to decrease gradually, reaching 120 kPa in the sixth month. When the applied voltage was increased to 15 V, the pwp decreased in the first 2 months from the previous ratio of voltage, then it began to decrease gradually and reached 70 kPa in the sixth month. When the applied voltage was further increased to 30 V, the pwp in the soil decreased in the first 2 months from the previous ratios of voltages, then it began to decrease gradually and reached 40 kPa. The percentage of water leaving the soil when an electric current of 5–15 V was applied was 64%. When the voltage was increased to 15–30 V, the value became 75%. That is, as the applied voltage increased, more water was discharged from the soil. The soil settlement also increased with an increase in voltage. The improvement percentage and the percentage of water leaving the soil were 50% at 5–15 V and 71% at 15–30 V.

1. Introduction

Most of central and southern Iraq's soil varies from soft to very soft and clayey soil, especially in areas near marshes. In these areas, several projects are planned. More than 1,400 km of a new railway network is expected to be created, and the existing network will be repaired [1]. Clay is a fine-grained natural soil or rock material, and its volume changes considerably when subjected to load. The water content of clay may be greater than its liquid limit. However, clay is plastic due to the influence of high moisture content and becomes nonplastic and

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hard after drying [2]. This increase in moisture content may come from rain, flood, sewer, leaks or surface reduction evaporation when buildings or sidewalks cover an area. Clayey soil mainly causes cracking and fracturing of pavement, railway, highway embankments, roads, foundations and channel or reservoir lining [3].

The water content between the plastic limit and semisolid is called plastic limit, and the shrinkage limit is the state in which the loss of water does not cause any volume change [4].

Water can significantly impact a soil's ability to remain stable. Given that soil stability and strength depend on effective stress, changes in pore water pressure directly affect these properties. Dewatering is a method for altering soil's water content and pore water pressure to improve soil behaviour. It can be done using prefabricated vertical drains, surcharge or preloading to improve soft soil. Vertical sand or gravel drains can also be used [5].

Granular columns are widely used in geotechnical engineering to reduce settlement, increase bearing capacity, accelerate consolidation and decrease liquefaction potential [6]. In a previous study, a model was evaluated on granular columns with and without reinforcement at various depths, including short, floating and fully penetrated columns. The column appeared to be in failure mode because of the diverse configurations and reinforcements used, exhibiting a minimal difference. The authors concluded that providing encasement is the optimum solution for end-bearing columns, but horizontal strip reinforcement and encasement for floating columns have no effect [7]. The footing load was given using a sand mat in a temperature- and humidity-controlled setting, and the column was placed at the centre of a massive tank. The authors discovered that long stone columns (reinforced or unreinforced) always failed by bulging, whereas floating or end-bearing stone columns always failed by punching.

Under embankment loading, the behaviour of completely reinforced and unreinforced clay and geogrid-encased columns was statistically examined. The clay's behaviour was studied through consolidation analysis. The foundation's bearing capacity increased when the surplus pore water pressure was lowered, with increased utility with encased columns. Whether the stress concentration created in columns has a significant impact on soil consolidation speed was also examined [8].

Porous water can be transferred from a positive electrode to a cathode along with other materials by providing an external electric field to the soil mass. Unification occurs because of the magnetic movement of cations. Many field tests and laboratory experiments have been conducted for this technology [9].

Electro-osmotic consolidation has been utilised frequently in geotechnical engineering since Casagrande (1949) initially employed it to increase the stability of fine soils, notably during slope stabilisation, soft ground improvement, tailing dewatering, sludge treatment and other processes [10].

Reference [11] constructed a 2D finite difference model by analysing subsurface settlement and undrained shear quality to quantify excess pore water weight during electro-osmosis. When cathodes were introduced vertically, the anode's impact was similar to that of a relocated column, such as a vibro-compacted stone column. The excess pore weight produced at the anode by the voltage contrast was similar to the increase in spiral stretch caused by the installation of a granular column. Thus, a lattice of anodes and cathodes set vertically could have an effect similar to that of a lattice made of stone columns.

Reuss first described the principle of electro-osmosis in 1809. He observed that water flowed through the clay when a direct current was applied, as shown in Fig. 1 [12].

From [13], water will flow from the anode to the cathode with the influence of the applied potential. This flow is attracted by anions to the anode and cations to the cathode. During the migration process, the moving ions will carry the surrounding water for hydration because the cations in the negatively charged clay particles are much higher than anions; therefore, pore water is drawn from the anode to the cathode. Electro-osmosis depends on electro-osmotic conductivity and applied voltage.

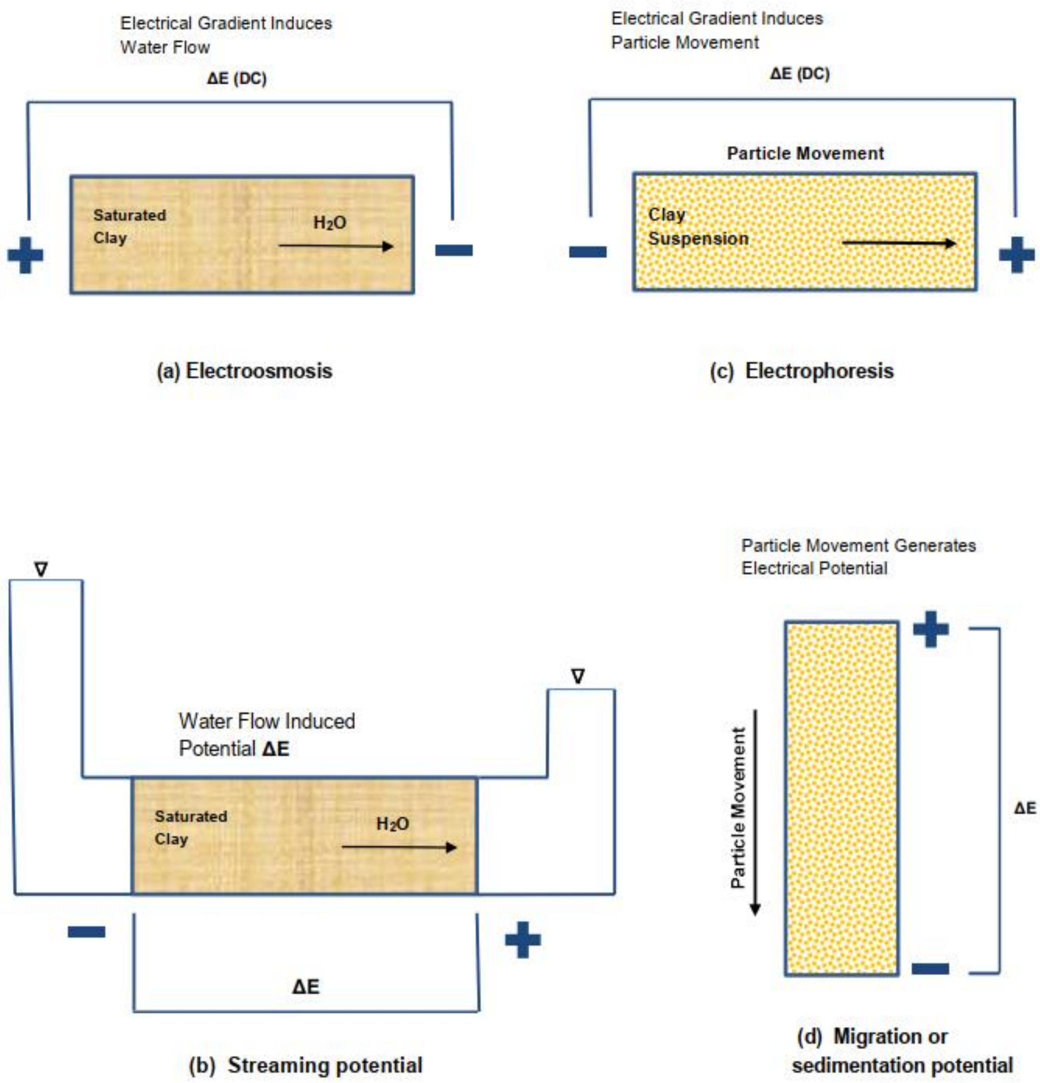


Figure1. Electro-osmosis phenomena in soil [12]

A numerical model of the electro-osmosis setup was created for this work. To calculate the temporal progression of the weight, electric field, pore water pressure, settling and distortion within the soil and columns planted in it as a result of the connected stack, this study created an FE view in this manner to simulate electro-osmosis through two geometric measurements.

2. Methodology

2.1 Soil material

A model was created for the simulation of soft soil to be treated with granular columns and electric current to speed up the process of water leaving the soil in a period of 6 months. FE analysis was executed using the COMSOL programme. A numerical model with dimensions of (8*6) m² was used to create a soft clay soil, as shown in Fig. 3. Granular columns of 8 m in length and 1 m in diameter were inserted, along with anode and cathode electrodes of 4 m in length and 0.1 m in diameter embedded in the granular columns. The voltages applied were 5, 15 and 30 V, and the load applied to the soil was an earth dam (36 kN/m²). The boundary conditions of this domain were fixed in the bottom, in the right and left rollers and in the top boundary load. Fig. 4 shows the fine mesh of the soil structure with granular columns, and the material properties are listed in Table 1 [14].

2.2 Concept of Electro-Osmosis

Electro-osmosis is the process by which an electric current causes a stream of pore fluids in soil. The electro-osmosis principle is depicted in Fig. 2 [15]. The electrolysis process is influenced by the chemistry of soil water, gas generation and electrolytic redox productivity.

Owing to the voltage difference between a positive anode and a negative cathode, voltage refinement recreates a negative pore weight combination caused by an outside stack at the anode inside the soil. The degree of union will alternate between the cathode and anode, with the anode taking the lead because the anode is closed, meaning no pore liquid regeneration occurs, and the cathode functioning as a depleter. If anodes are introduced vertically, the effect around the anodes can be compared with the impact of a relocation column, such as a vibro-compressed granular column [16]. Calculative analysis was carried out using COMSOL Multiphysics, a finite element tool. A multifield coupling numerical simulation of electro-osmotic solidification was performed. The condition for pore water was as follows:

$$\nabla.(Kh\,\nabla H + Ke\,\nabla V) = -\frac{\partial \varepsilon v}{\partial t} = \frac{\partial}{\partial t}(\nabla.u) \qquad (1)$$

where Kh and Ke are the pressure-driven conductivity and electro-osmosis conductivity tensors, respectively; H and V are added up to the water head and voltage, respectively; εv is the volumetric strain of soil mass; u is the vector of soil mass uprooting. Biot's theory characterises the stress–strain behaviour of soil [17].

$$\nabla^2 u + \frac{1}{1-2v}(\nabla.u) - \gamma w.\frac{2(1+v)}{E}\nabla(H-z) = 0 \qquad (2)$$

where v is Poisson's proportion, E is Young's modulus, z is the height head, and γw is the water unit weight. The law of conservation of electrical charge can be utilised to determine the overseeing condition for the electric field.

$$\Sigma e \nabla^2 V = Cp\frac{\partial v}{\partial t} \qquad (3)$$

where σe is the electrical conductivity tensor, and Cp is the capacitance per unit volume.
Eqs. 5–7 were combined to explain the electro-osmotic consolidation linked process.

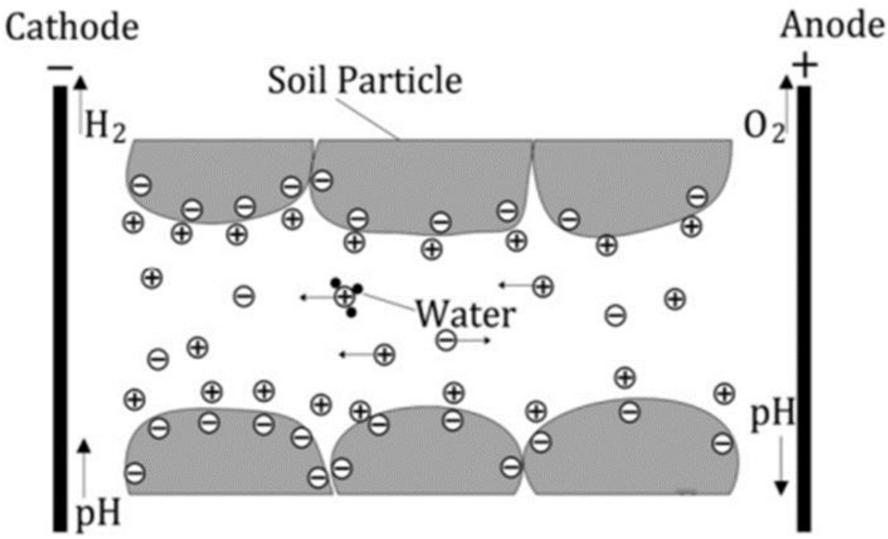


Figure 2. Principles of electro-osmosis [15]

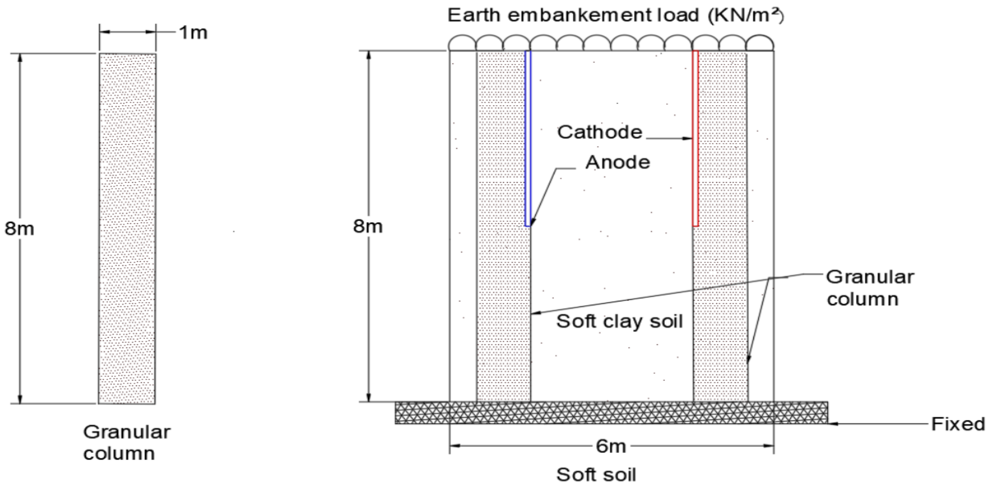


Figure 3. Geometry modeling of soft clay soil embedded granular column [14]

Table 1: Material soil parameters adopted for FEM analysis [14]

Parameter	Units	Soft soil	Granular columns
Material model loading	_	MC Undrained	MC Drained
Young's modulus	(kN/m²)	2000	55000
Poisson's ratio	(v)	0.4	0.3
γunsat	(kN/m³)	15	18
γsat	(kN/m³)	16	19
Porosity	_	0.5	0.3
Compressibility of fluid	(1/Pa)	0.001	0.001
Horizontal permeability Kh	(m/day)	7.36×10^{-5}	12
Vertical permeability Kv	(m/day)	3.68×10^{-5}	6
Relative permittivity	_	0.9	1
Cohesion	(kN/m²)	35	0
Friction angle	(φ°)	1	35

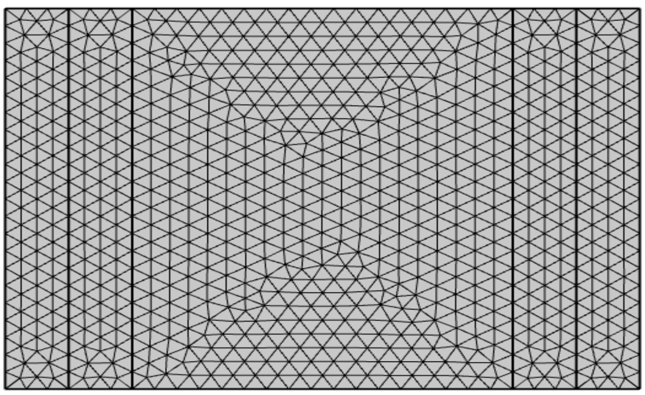


Figure 4. Finer mesh of geometry soft soil model and granular column

3. Results and discussion

Given that soil stability and strength depend on effective stress, changes in pore water pressure directly affect these properties. Electro-osmosis is a method for altering the water content and pore water pressure of soil to improve soil behaviour. A granular column with electro-osmosis can be used to improve soft soil. A porous material that has been soaked in water will migrate towards the negative electrode (cathode) when a direct current is supplied to it; this occurrence is known as electro-osmosis. The ions with positive charges produced by applying a direct current will cause the water in the soil's pores to flow out. Because water cannot access the system's anode (positively charged electrode), the soil's water content decreases. Consequently, the soil is consolidated. Given its ability to reinforce soft, saturated clayey soil and expedite consolidation, electro-osmosis has an advantage over other methods [18].

Figure 5 shows the relationship between pore water pressure and time in months for granular columns with a length of 8 m and a diameter of 1 m. The slenderness ratio of these curves is L/D=8. Because of the pressure effect from the applied load with an applied electric current of 5 V, the pore water pressure begins to rise until it reaches the highest point, then it begins to descend gradually and reaches the lowest value in the sixth month. The water drains from the soil because of the length of the granular column, which shortens the path of water drainage in addition to shedding electric current.

The second curve shows the pore water pressure when the voltage is increased to 15 V for the electric current between the electrodes (anode and cathode) planted inside the granular columns in soft soil. It demonstrates a decrease in pore water pressure from the previous voltage curve (5 V). Thus, when the applied voltage increases, the drainage of water from the soil increases faster.

The third curve shows the pore water pressure of soft soils when the applied voltage is increased to 30 V and granular columns are embedded in a period of six months. The pore water pressure of the soft clay soil treated with granular column and electric current is small compared with the pore water pressure from the previous voltage because the current is applied with a high voltage. The application of potential between the anode and the cathode leads to an increase in the concentration of negative ions from positive ones because the surface of the clay particles is negative, causing the drainage of water.

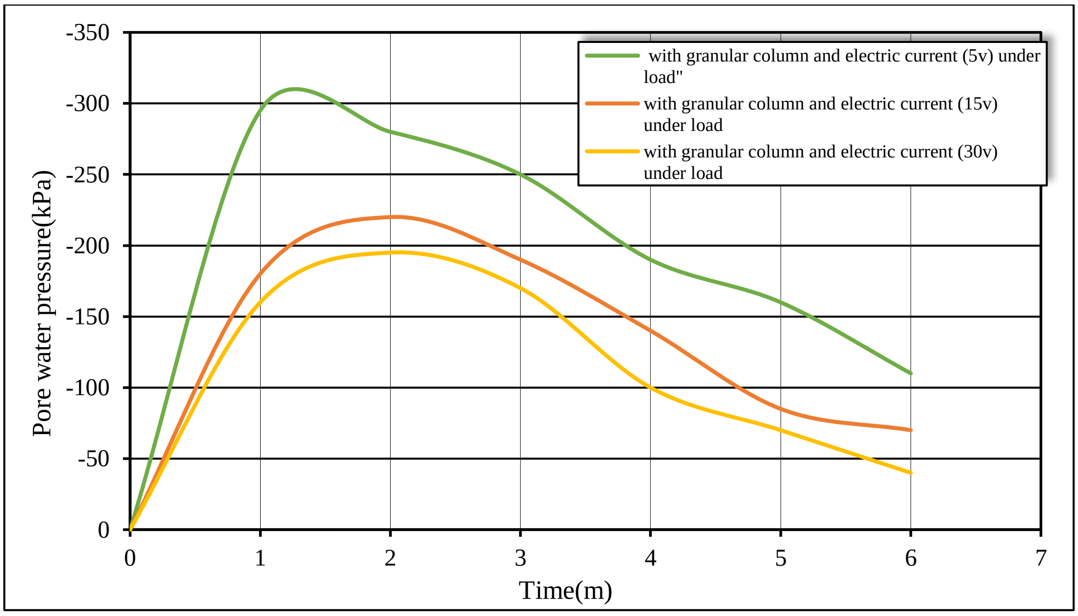
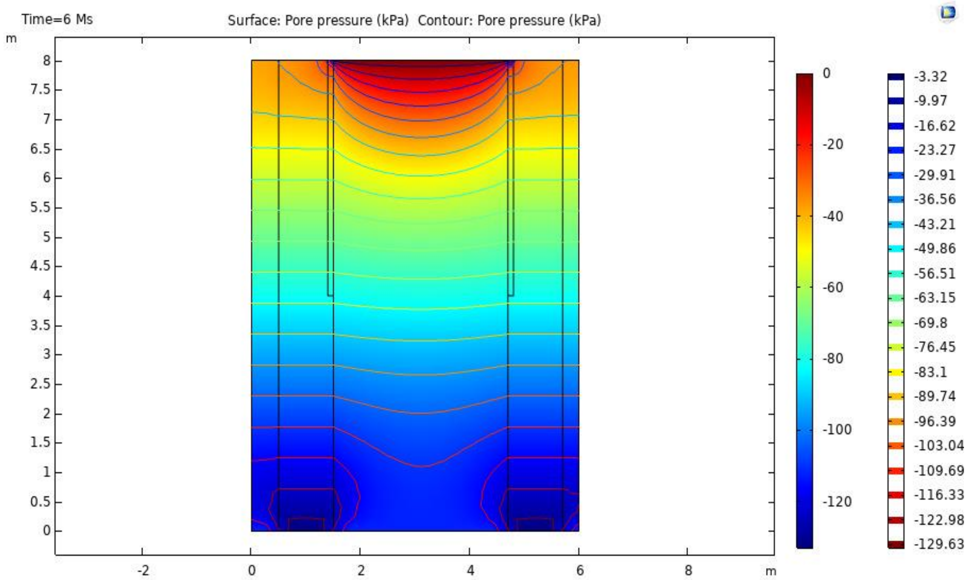
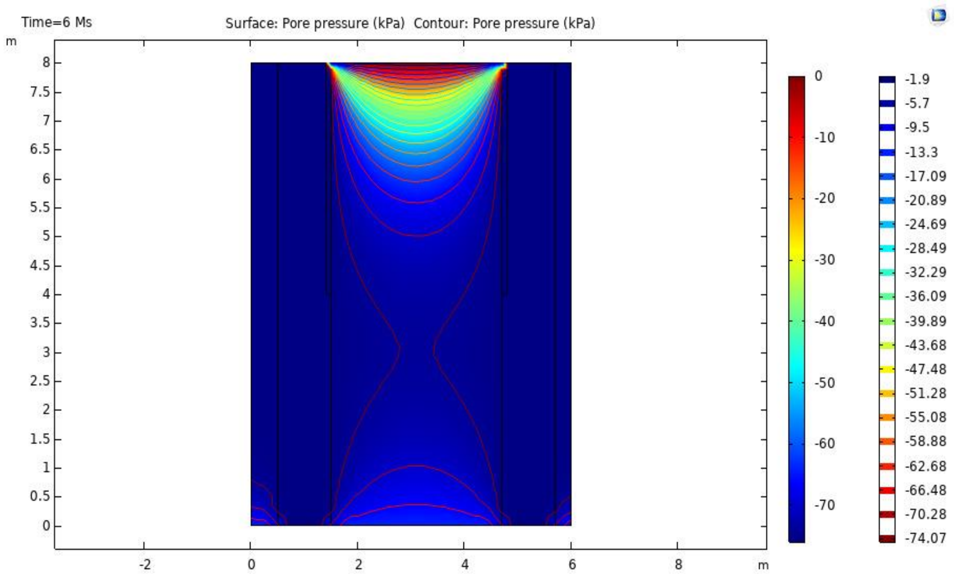


Figure 5. Time pore water pressure relationship of soft soil treated by granular column and electric current for (5,15, and 30v)

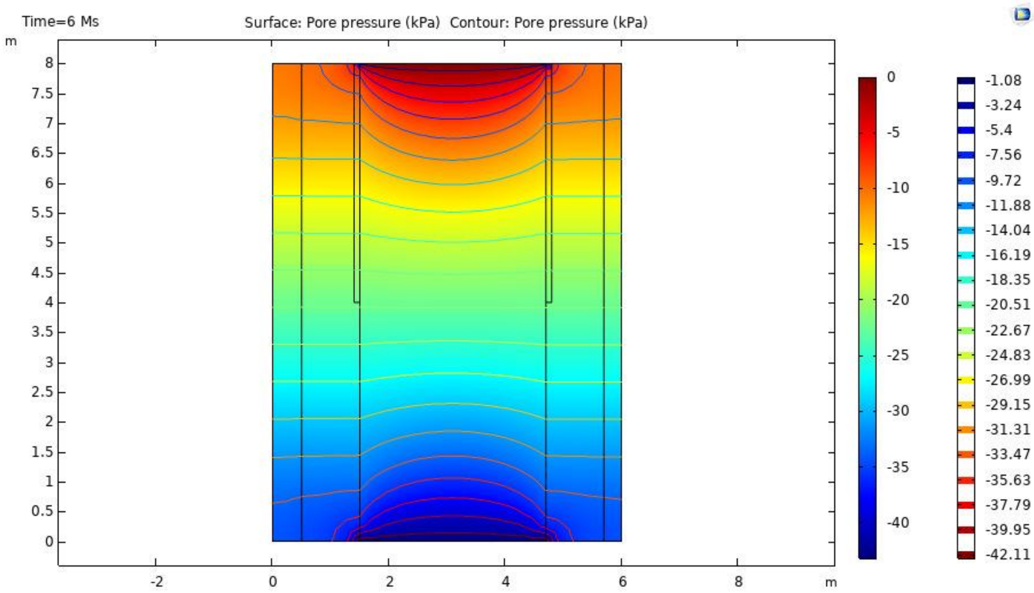
In Figure (6. a), the contour lines show the pore water pressure distribution in soft soils when an electric current of 5 V is applied. The distances between the lines are short in the first 2 m from the soil surface due to the influence of pressure from the applied load, in addition to electric current shedding. This condition accelerates the exit of water from the soil. Then, it expands, and its value increases until it reaches the end of the soil because of the lack of its effect caused by the pressure from the load imposed on it. In Figure (6. b), the contour lines show the distribution of pore water pressure in soft soils when an electric current of 15 V is applied. The increase in the applied voltage leads to an increase in the pressure of the lines expressing the pressure of water molecules in the first 2 m of the soil surface, in addition to the effect of the soil by the applied load. Then, the lines become less affected from the contour in the depth of the remaining soil to the end. In Fig. (6.c), the contour lines show the distribution of pore water pressure in soft soil when an electric current of 30 V is applied. The lines expressing the pressure of water molecules accumulate in the first meter of the soil surface, in addition to the influence of the soil by the applied load. Afterwards, the effect of the contour lines in the remaining soil depth decreases up to its end, and the values of pore water pressure decrease. Therefore, water from the soil drains more with increasing applied voltage.



(a)



(b)



(c)

Figure 6. Relationship between pore water pressure with depth in six months for: (a)at five voltages, (b) at fifteen voltages, (c) at thirty voltages

Figure 7 shows the relationship between soil settlement and the time of 6 months for soft soil containing granular columns with an electric current of various voltages (5, 15 and 30 V). The first curve represents the soil settlement when a current of 5 V is applied. The settlement increases gradually over time until it reaches the highest value of 0.2 m in the sixth month. The second curve presents the soil settlement at 15 V. The settlement increases over the previous curve with the increase in the applied voltage, and its value reaches 0.4 m in the sixth month. When a current of 30 V is applied, the soil settlement increases slightly over the preceding curve and reaches its highest value of 0.56 m in the sixth month. The increase in voltage leads to an increase in the drainage of water from the soil, which is the reason for the increase in its settlement. However, its effect is less when its value is increased over 25 V.

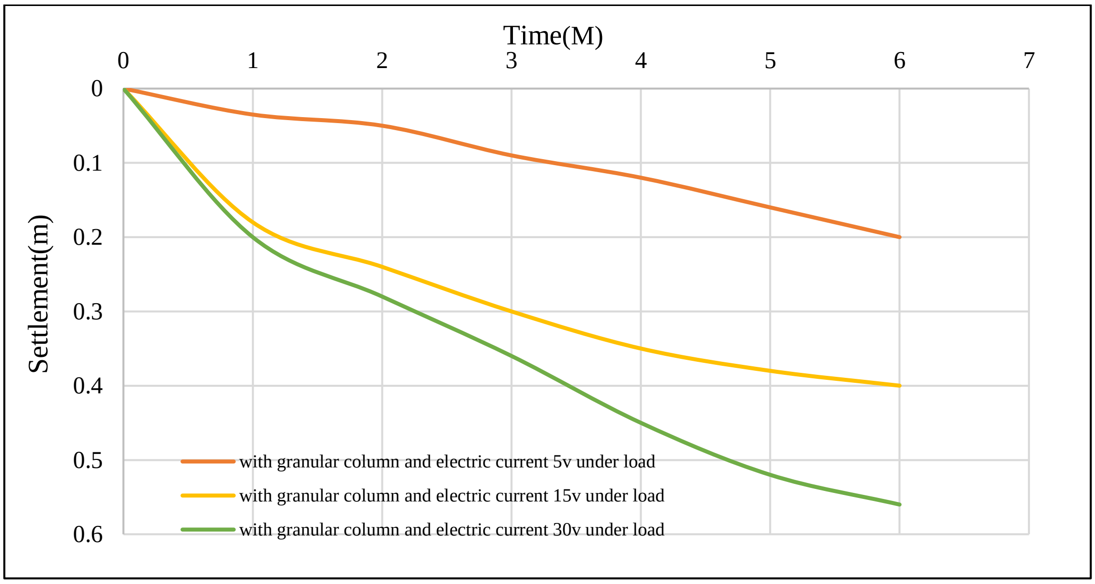


Figure 7. The relationship between time and settlement of soft soil with granular column and electric current of (5,15, and 30v)

To verify the programme, Fig. 8 shows the results of pore water pressure obtained using the current soil model with a granular column but without electric current applied. The time period is 1–1000 days. The results agree with other solutions and are reasonably close to those of Elsawy (2010) who conducted field tests on a highway embankment constructed on soft soil improved by granular columns in Aswan, Egypt.

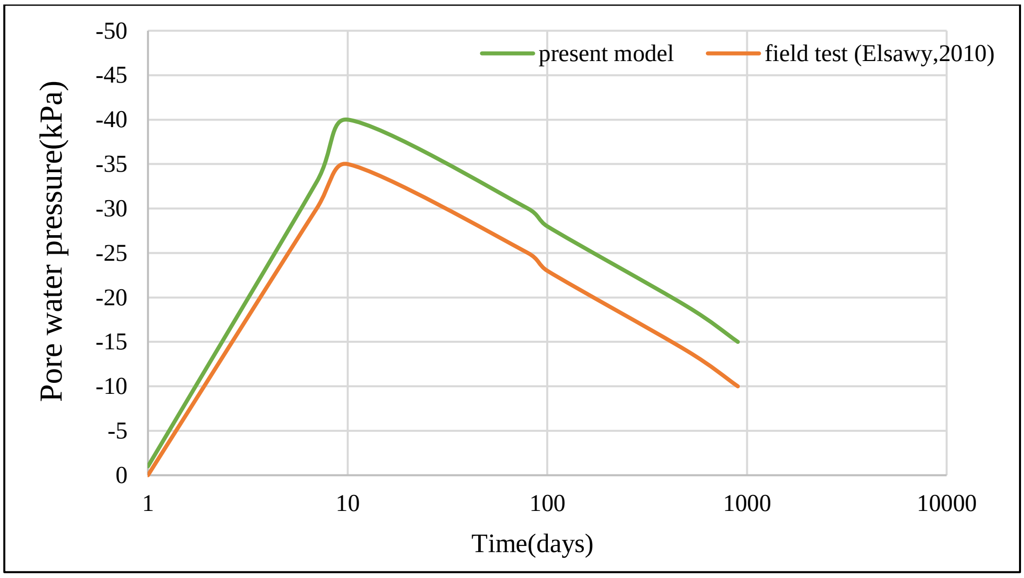


Figure 8. The pore water pressure of the present model and field test

4. Conclusions

A numerical model for the electro-osmosis treatment analysis of soft clay was used to simulate the pore water pressure in soft clay soil due to electro-osmosis technology. The soil and granular column responded to the electric current applied to them and improved after 6 months of water disposal in it. The pressure of the water molecules in the soil decreased after the electric field between the anode and cathode was spilled at high voltages. The results were as follows:

1. When the electric current was applied with a voltage of ٥ V, the pore water pressure in the soil increased in the first 2 months, reaching 300 kPa. Then, the pressure began to decrease gradually, reaching 120 kPa in the sixth month, which meant that water came out of the soil slowly.
2. When the applied voltage was increased to 15 V, the pressure of the water molecules in the soil in the first 2 months decreased from the previous ratio of voltage, reaching 220 kPa. The value then began to decrease gradually and reached 70 kPa in the sixth month. the increase in voltage led to a decrease in the pore water pressure to drain the water from the soil.
3. When the applied voltage was increased further to 30 V, the pore water pressure in the soil in the first two months decreased from the previous ratios of voltages, reaching 190 kPa. Afterwards, it gradually decreased and approached 40 kPa in the sixth month. That is, the higher the applied voltage, the more water was discharged from the soil.
4. The percentage of water leaving the soil when an electric current of 5–15 V was applied was 64%. When the applied voltage was increased to 15–30 V, the value became 75%. Hence, as the applied voltage increased, more water was discharged from the soil.
5. The soil settlement increased with an increase in the applied voltage. The improvement percentage and the water discharged from the soil were 50% at 5–15 V and 71% at 15–30 V.

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