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Yang, S, Jianting, F, Chenchen, Q et al. (1 more author) (2020) Two-Dimensional Consolidation Theory of Vacuum Preloading Combined with Electroosmosis Considering the Distribution of Soil Voltage. Soil Mechanics and Foundation Engineering, 57 (1). pp. 25-34. ISSN 0038-0741

https://doi.org/10.1007/s11204-020-09633-8

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Soil Mechanics and Foundation Engineering, Vol. 57, No. 1, March, 2020 (Russian Original No. 1, January-February, 2020)

SOIL MECHANICS

TWO-DIMENSIONAL CONSOLIDATION THEORY OF VACUUM PRELOADING COMBINED WITH ELECTROOSMOSIS CONSIDERING THE DISTRIBUTION OF SOIL VOLTAGE

UDC 624.023.943

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It is necessary to consider the influence of the actual soil voltage distribution when establishing the consolidation equation to more realistically reflect the soil consolidation conditions during the vacuum preloading and electroosmosis process. The distribution of the soil voltage is analyzed by integrating previous results with independent experimental findings. The equation for the dissipation of the excess pore water pressure and the soil consolidation equation are derived based on the proposed model with a closed anode and an open cathode, and the analytical solution is verified by a model test. The results show that the measured excess pore water pressure values coincide with the calculated values, thereby proving the rationality of the consolidation equation established in this paper.

Introduction

Land reclamation is often employed to expand urban areas to mitigate the imbalance between population growth and land for residential construction. However, the moisture content of soft clay and dredged clay after dredging is usually 100%~200%. Such soil, which is characterized by a high moisture content, high compressibility, low permeability and low bearing capacity, cannot meet construction requirements. Therefore, it is necessary to process land composed of dredged super soft clay to let the soil satisfy or exceed the requirements of engineering projects.

Although soft soil foundations can be rapidly and extensively processed by the vacuum preloading method, the vacuum degree will decrease gradually as the soil depth increases. Consequently, the processing effect will be poor for deeper soil, and thus, it is often necessary to process such soil a second time before initiating construction [1-3]. In contrast, the electroosmosis method exhibits remarkable results in the processing of soft foundations; however, this technique has not been applied broadly because the electrodes corrode easily, the energy consumption is excessively high, and the strength of the reinforced soil is non-uniform [4-8]. Accordingly, several engineering technologies have been utilized in conjunction with electroosmosis to further improve the foundation reinforcement effect, resulting in the emergence of vacuum preloading combined with electroosmosis.

The method of vacuum preloading combined with electroosmosis is effective for processing soft soil foundations because the integration of these two technologies can take advantage of their strengths while avoiding their weaknesses. The vacuum preloading drainage velocity can be improved by using electroosmosis, and the discharge of gas that gathers at the electrodes can be accelerated by vacuum preloading. Moreover, the combination of these two methods can effectively reduce cracks and enhance the contacts between the electrodes and soil, greatly improving the electroosmosis efficiency. A multitude of

Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 1, p. 13, January-February, 2020.

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experiments have been carried out on the method of vacuum preloading combined with electroosmosis by many domestic and foreign scholars [9-13]. In addition, this combined method has also been investigated and refined by scholars from a theoretical perspective to further prove its validity. Based on K. Terzaghi's consolidation theory and M. I. Esrig's electroosmosis consolidation theory, W. Xu deduced a two-dimensional consolidation equation for soft foundations strengthened with the method of vacuum preloading combined with electroosmosis [14]; furthermore, an analytical solution was presented for the excess pore water pressure in the process of applying the method of vacuum preloading combined with electroosmosis. H. Wu developed an axisymmetric analysis model for the processing procedure of the method of vacuum preloading combined with electroosmosis; a theoretical deduction was also presented in addition to a numerical simulation analysis [15]. J. Li established an equation for the consolidation of soft foundations under axisymmetric vacuum preloading combined with electroosmosis and deduced an analytical solution for the mean pore pressure and degree of radial consolidation in soft foundations. This was accomplished by considering the superposition of electroosmosis flow and pressure flow and merging S. Hansbo's consolidation theory for drained fine-grained soils with the boundary conditions of vacuum preloading combined with electroosmosis; in addition, a degenerate verification was also performed [16]. Similarly, based on K. Terzaghi's and M. I. Esrig's theories, Y. Shen established a vertical two-dimensional plane drainage model of vacuum preloading combined with electroosmosis; the analytical solution is derived to describe the behavior of excess pore water and process of consolidation with the usage of EKG materials, which integrates drainage and conduction in consideration of a rectangular arrangement of electrodes and the vacuum smearing effect [17].

However, the above-mentioned theoretical and numerical studies and other existing electroosmosis consolidation theories assume that the soil voltage distribution is linear [18-21]. Consequently, there are some inconsistencies between this assumption and laboratory test results. For example, based on previous experimental results, the soil voltage will jump at the electrodes during the method of vacuum preloading combined with electroosmosis due to the contact resistance between the electrodes and the soil. Accordingly, it is unreasonable for theoretical derivations to assume that the soil voltage is linearly distributed. Therefore, to more realistically reflect the actual soil consolidation conditions during the application of vacuum preloading combined with electroosmosis, the actual distribution of the soil voltage during this process is studied in this paper. Anodic electrodes are taken as the research object, following which a horizontal two-dimensional plane model is established for the method of vacuum preloading combined with electroosmosis; then, based on the proposed model, the dissipation equation for the excess pore water pressure and the soil consolidation equation are deduced in consideration of the soil voltage distribution. Finally, the equations are verified by a laboratory model test, thereby proving the rationality of the equation providing a new theoretical reference for the further popularization and application of the method of vacuum preloading combined with electroosmosis.

Distribution Law of Soil Voltage

In recent years, laboratory tests have shown that the soil voltage is not linearly distributed during the process of vacuum preloading combined with electroosmosis. Accordingly, to more realistically reflect the consolidation of the soil during the vacuum preloading and electroosmosis process, it is necessary to consider the influence of the actual soil voltage distribution when establishing the consolidation equation for the combined technique.

Accordingly, this paper integrates the data published in recent years in geotechnical journals on the soil voltage distribution between cathode and anode electrodes during experimental researches on the method of vacuum preloading combined with electroosmosis [22, 23]. In addition, soil voltage distribution data are obtained from experimental studies [24]. Consequently, four sets of soil voltage distribution data acquired during the application of vacuum preloading combined with electroosmosis under four different voltages are obtained.

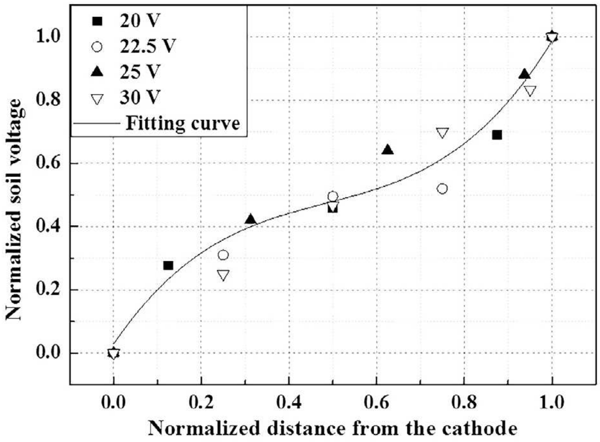

Fig. 1. Normalized soil voltage distribution.

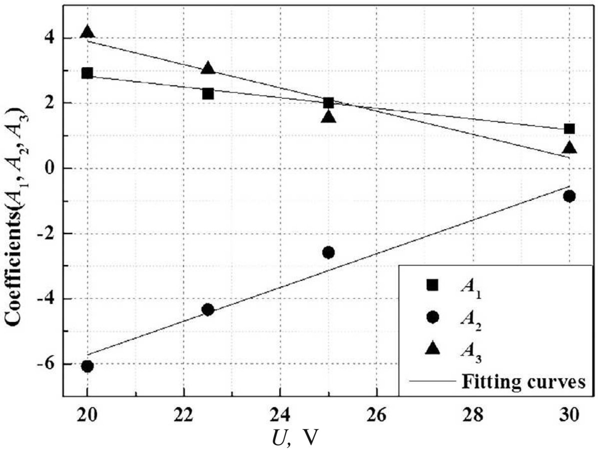

Fig. 2. Relationships between the parameters and the output voltage.

The test data are first normalized, and the results are shown in Fig. 1. Upon analyzing the related test data, the normalized soil voltage distributions clearly change following evident curves. Then, cubic polynomials are used to fit the data obtained under different output voltages. Subsequently, relationships are obtained between the normalized soil voltage and the normalized distance from the cathode under power supplies with different output voltages. These relationships can be written as

$$\text{20 V:}\quad U' = 2.921x' - 6.074x'^2 + 4.153x'^3; \tag{1}$$

$$\text{22.5 V:}\quad U' = 2.284x' - 4.334x'^2 + 3.04x'^3; \tag{2}$$

$$\text{25 V:}\quad U' = 2.017x' - 2.86x'^2 + 1.55x'^3; \tag{3}$$

$$\text{30 V:}\quad U' = 1.21x' - 0.83x'^2 + 0.5979x'^3, \tag{4}$$

where U' is the normalized soil voltage and x' is the normalized distance from the cathode ($0 \le x' \le 1$, $0 \le U' \le 1$). The R^2 values fitted to the four different output voltages are 1, 0.9883, 0.9989, and 0.9909. The results demonstrate that the actual soil voltage distributions can be effectively reflected by cubic polynomial fitting curves. Therefore, it is assumed that the normalized soil voltage distribution under any output voltage can be expressed as

$$U' = A_1x' + A_2x'^2 + A_3x'^3, \tag{5}$$

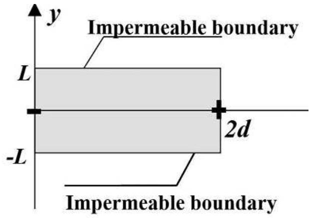

Fig. 3. Computing model of the proposed method.

where $A_1 = -0.1645U + 6.1172$, $A_2 = 0.5172U + 16.069$, and $A_3 = -0.3573U + 11.043$ are the parameters related to the output voltage, U is the output voltage (Fig. 2).

The fitted R^2 values between A_1, A_2, and A_3 and the output voltage are 0.9820, 0.9652, and 0.9387, respectively.

Establishing Consolidation Equation

Considering a rectangular arrangement of cathodes and anodes in the practical engineering application of the method of vacuum preloading combined with electroosmosis in conjunction with the two-dimensional consolidation theory of electroosmosis proposed by J. Q. Su [25], this paper takes the anodic electrode as the research object. Accordingly, a horizontal two-dimensional plane model that more closely reflects the real engineering conditions is established; the computing model is shown in Fig. 3.

The proposed model provides a reference for the subsequent derivation of the dissipation equation for the excess pore water pressure and the soil consolidation equation in the method of vacuum preloading combined with electroosmosis under the planar two-dimensional strain model considering a closed anode and an open cathode.

The following assumptions should be made to establish the two-dimensional consolidation equation for the method of vacuum preloading combined with electroosmosis.

1. The only factor that should be considered is the horizontal seepage of the soil. The upper and lower boundaries are impermeable, and the water flows caused by the voltage difference and head difference can be superimposed.
2. Soil is fully saturated and homogeneous. The compression of soil is the result of skeletal deformation caused by a decrease in the pore volume. The decrement of soil particles and pore water during the process of consolidation can be neglected. The amount of drainage discharged from a unit cell of soil is equal to the decrease in the soil volume.
3. Water flows caused by various ion concentrations and temperature differences can be ignored.
4. Vacuum is applied instantaneously. The well resistance of vertical drains and smear effects are neglected.

The drainage velocity of the method of vacuum preloading combined with electroosmosis at the cathode and anode electrodes is the superposition of the hydraulic seepage velocity caused by vacuum suction and the electroosmosis velocity caused by electroosmosis:

$$\text{anode } v = k_h i_h - k_e i_e \text{ and cathode } v = k_h i_h + k_e i_e, \tag{6}$$

where v is the velocity of flow, k_h is the hydraulic permeability in the horizontal direction, k_e is the electroosmosis permeability, i_h is the hydraulic gradient, and i_e is the voltage gradient.

The above equation are deduced under the condition of an open cathode. The hydraulic and electroosmosis seepage are superposed at the cathode. For the model, the flow of pore water occurs in both the x and the y directions as the result of the simultaneous action of hydraulic and electrical gradients. The difference in the water quality between the inflow and outflow of an arbitrary volume aquifer in the two-dimensional plane is equal to the variation in the water quality within that volume based on assumption (2) and K. Terzaghi's consolidation theory.

Accordingly, the volume of excess pore water can be expressed as follows. The difference between the inflow and outflow

in the x direction is

$$\frac{(\rho v_x)|_{(x,y,t)} - (\rho v_x)|_{(x+\Delta x,y,t)}}{\Delta x}\Delta x\Delta y\Delta t = -\frac{\partial(\rho v_x)}{\partial x}\Delta x\Delta y\Delta t; \tag{7}$$

in the y direction is

$$\frac{(\rho v_y)|_{(x,y,t)} - (\rho v_y)|_{(x,y+\Delta y,t)}}{\Delta y}\Delta x\Delta y\Delta t = -\frac{\partial(\rho v_y)}{\partial y}\Delta x\Delta y\Delta t. \tag{8}$$

The aquifer is regarded as a rigid body. If the water and medium do not experience elastic deformation, the seepage is stable. Therefore, the continuity equation of seepage under the action of hydraulic seepage can be written as

$$div(v) = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = m_v\frac{\partial u}{\partial t}, \tag{9}$$

where m_v is represents the soil volume compressibility parameter, t is the test time, and u is the excess pore water pressure. Similarly, the continuity equation of excess pore water flow driven by an electric field force can be obtained as follows:

$$div\left(v\right) = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = C_p\frac{\partial \varphi}{\partial t}, \tag{10}$$

where C_p is the capacitance of soil per unit volume, and φ is the voltage. This equation represents the current generated by an applied electric field within the soil. Combining Eqs. (9) and (10) to superpose the equations of hydraulic seepage and electroosmosis seepage, the variations in the pore water inflow and outflow in the x and y directions can be obtained as follows:

$$Q_{hx} = \frac{k_{hx}}{\gamma_w}\frac{\partial u}{\partial x} + k_e\frac{\partial \varphi}{\partial x}, \tag{11}$$

$$Q_{hy} = \frac{k_{hy}}{\gamma_w}\frac{\partial u}{\partial y} + k_e\frac{\partial \varphi}{\partial y}. \tag{12}$$

Thus,

$$div\left(v\right) = \frac{\partial Q_{hx}}{\partial x} + \frac{\partial Q_{hy}}{\partial y} = m_v\frac{\partial u}{\partial t}. \tag{13}$$

Combining Eqs. (11), (12), and (13),

$$\frac{k_h}{\gamma_w}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + k_e\left(\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2}\right) = m_v\frac{\partial u}{\partial t}; \tag{14}$$

$$\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + k_e\frac{\gamma_w}{k_h}\left(\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2}\right) = m_v\frac{\gamma_w}{k_h}\frac{\partial u}{\partial t}. \tag{15}$$

The voltage distribution between the anode and the soil adjacent to the anode can be expressed as

$$\varphi(x,y,t) = \left(A_1\frac{x}{2d} + A_2\frac{x^2}{(2d)^2} + A_3\frac{x^3}{(2d)^3}\right)U. \tag{16}$$

Then, assuming a dummy variable, the following equation can be written:

$$\xi(x,y,t) = u(x,y,t) + \frac{k_e\gamma_w}{k_h}\varphi(x,y,t). \tag{17}$$

The control equation of the computational model can be obtained by bringing ξ into Eq. (15):

$$\frac{\partial \xi}{\partial t} = C_h \left(\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2} \right), \tag{18}$$

where $C_h = k_h / m_v \gamma_w$ is the horizontal consolidation parameter of soil.

The vacuum of the outlet p_0 during the process of vacuum preloading combined with electroosmosis. The boundary conditions can be summarized as follows:

open cathode: $x = 0$, $y = 0$, $u = -p_0$, $\varphi = 0$

$$\xi(0,\ 0,\ t) = -p_0; \tag{19}$$

closed anode: $\xi_x + \xi_y = 0$,

$$\xi_x(2d,\ 0,\ t) + \xi_y(2d,\ 0,\ t) = 0; \tag{20}$$

impervious boundary at $y = \pm L$

$$\xi_y(x,\ \pm L,\ t) = 0. \tag{21}$$

The initial condition is

$$\xi(x,y,0) = u(x,y,0) + \frac{k_e \gamma_w}{k_h} \varphi(x,y,0). \tag{22}$$

From Eqs. (16)-(22),

$$u(x,y,t) = -p_0 - \frac{k_e \gamma_w}{k_h} \varphi(x,y,t) + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} a_{mn} \sin \frac{(2m-1)\pi x}{4d} \sin \frac{(2n-1)\pi y}{2L} \exp(-(-\lambda + \mu) C_h t, \tag{23}$$

where

$$a_{mn} = \frac{8 p_0}{(2m-1)(2n-1)\pi^2} - \frac{64 k_e \gamma_w U A_2}{k_h (2m-1)^3 (2n-1)\pi^4} - \frac{394 k_e \gamma_w U (-1)^{m-1} A_3}{k_h (2m-1)^4 (2n-1)\pi^5} + \frac{16 k_e \gamma_w U (-1)^{m-1} (3A_3 + 2A_2 + A_1)}{k_h (2m-1)^2 (2n-1)\pi^3},$$

$\lambda = [(2m - 1)\pi/4d]^2$, $\mu = [(2n - 1)\pi/2L]^2$, $m = 1, 2, 3, \ldots$, and $n = 1, 2, 3, \ldots$, are the indices.

Finally, an expression for the average degree of consolidation at any depth between the cathode and anode in the process of vacuum preloading combined with electroosmosis can be obtained as follows.

$$\overline{U} = 1 - \frac{u(x,y,t)}{u(x,y,0)}. \tag{24}$$

Example Analysis

To verify the rationality of the consolidation equation deduced above in consideration of the actual soil voltage distribution, a model test of vacuum preloading combined with electroosmosis is carried out. Tabular EKG devices are used as the test electrodes. By monitoring the pore water pressure during the laboratory experiment, the analytical solution can be compared with the measured values.

For the model test, soil samples that represent typical cohesive soils were taken from a Nanjing construction site at which vacuum preloading was applied. The physical and mechanical properties of the soil samples and the main experimental parameters are: liquid and plastic limits 42.5% and 24.2%; plasticity index 18; silt and clay contents 19.8% and 80.2%; initial moisture content 50%; $k_h = 2\times10^{-8}$ m/s; $k_e = 5\times10^{-9}$ m²/s·V; $C_h = 8\times10^{-8}$ m²/s; applied voltage 27.5 V.

The test was conducted in a self-developed laboratory model (Fig. 4), the internal dimensions of which are 250 × 200 × 500 mm. The rated power of the vacuum pump is 750 W. The maximum voltage output is 72 V, and the maximum current output is 3 A. Two small grooves are located at the bottom of the model that are used to fix the tabular EKG electrodes.

Test procedures are as follows. (1) An epoxy resin is smeared throughout the interior of the test model. (2) The tabular EKG devices (length of 420 mm) serving as the cathode and anode are connected

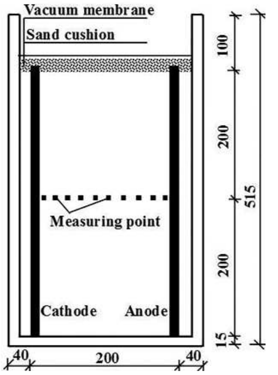

Fig. 4. Model device scheme.

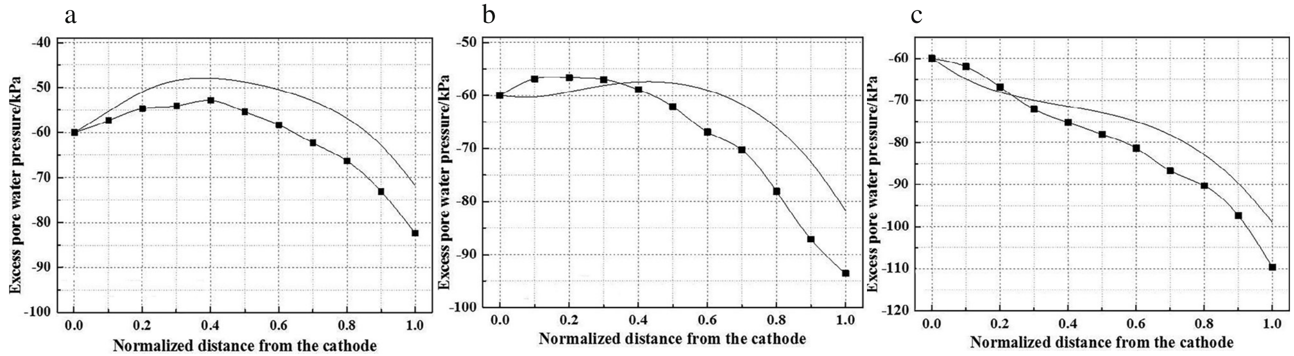

Fig. 5. Relationship between the excess pore water pressure and normalized distance at different times: a) t = 12 h, b) t = 24 h, c) t = 48 h; -■-) measured and ——) calculated values.

to the plate and tube connector and fixed at the bottom of the model. (3) The soil sample (thickness of 400 mm) is divided into four layers to make it denser. Each layer is filled and compacted carefully. (4) Several groups of pore pressure gauges are embedded at a depth of 200 mm at distances of 20, 40, 60, 80, 100, 120, 140, 160, and 180 mm away from the cathode and nearby electrodes. Due to the small size of the pore pressure gauges, the impact of their disturbance on the seepage field can be neglected. The pore pressure gauges are linked to the readout instrument through electric wires to record the data. (5) A sand cushion is laid on the surface of the soil sample. Then, the sand cushion is covered with a vacuum membrane to keep air from entering the test model. The outlet of the plate and tube connector is covered by a soft clay with a 30% moisture content, and the clay is backfilled and compacted. (6) The EKG electrodes are linked to the electric source through electric wires. The connector linked to the electrodes is connected with the drain pipe, and the drain pipe is linked to a vacuum saturation cylinder. Finally, an examination is carried out to guarantee that the test model is airtight.

Analysis of the Results

The voltage output in the model test was 27.5 V, thus, $A_1 = 1.59345$, $A_2 = -1.846$, and $A_3 = 1.21725$, respectively. The theoretical value of the excess pore water pressure can be obtained by Eq. (23). The calculated and measured values of the excess pore water pressure are plotted together in Fig. 5, which illustrates the distribution of the excess pore water pressure between the cathode ($x/2d = 0$) and anode ($x/2d = 1$) at t = 12, 24, and 48 h (y = 0.1 m). Overall, the values of the excess pore water pressure obtained in the laboratory tests are consistent with those obtained by theoretical calculations, thereby proving the rationality of the consolidation equation, which is based on the actual soil voltage distribution. In addition, the theoretically calculated values are identical to the values measured at the nearby cathode. In contrast, the measured excess pore water pressure near the anode is different from the theoretical calculation value. There are two main explanations for this discrepancy at the nearby anode. On the one hand, the temperature of the soil increased significantly near the anode, revealing the presence of an exothermic effect of electrolysis during the test. This change in the temperature will cause a change in the excess pore water pressure. On the other hand, the anodic tabular EKG experienced embrittlement, while the cathodic did not. This suggests that strong reactions occurred in the anode area during the application of vacuum preloading combined with electroosmosis, resulting in a change in the excess pore water pressure due to the chemical reactions of ions. However, the influences of the temperature field and ion reactions are neglected in the theoretical derivation. As a result, the measured values of the excess pore water pressure near the anode are different from the theoretically calculated values.

The excess pore water pressure distribution between the cathode and the anode is more uniform at t = 12 h and t = 24 h for both the calculated values and the measured values. This is because the excess pore water pressure develops from the anode and accelerates the consolidation of the soil near the anode when electroosmosis is applied alone. Meanwhile, vacuum preloading can accelerate the consolidation of the soil near the cathode. These advantages are united within the method of vacuum preloading combined with electroosmosis, which relatively homogenizes both the reinforcement effect and the distribution of the excess pore water pressure between the anode and cathode. Theoretically, these findings also demonstrate the advantages of the method of vacuum preloading combined with electroosmosis in dealing with soft soil foundations.

The distribution of the excess pore water pressure at t = 48 h is closer to that of the excess pore water pressure with electroosmosis alone because a substantial amount of water in the soil is discharged rapidly during the early stage under the combined action of vacuum preloading and electroosmosis. However, as the experiment continues, the moisture content of the soil decreases, and the efficacy of vacuum preloading gradually weakens. Moreover, the drainage effect becomes less remarkable. The drainage mainly depends on electroosmosis at the later stage. Therefore, the distribution of the excess pore water pressure is closer to that of the excess pore water pressure with electroosmosis alone.

Discussion

The consolidation equation derived in consideration of the actual distribution of soil voltage is established on the basis of the above-mentioned four assumptions. Many effects, such as electrical effects, electrical erosion effects, expansion effects, and electrolysis effects, are caused by the combined action of electroosmosis and drainage consolidation during the procedure of vacuum preloading combined with electroosmosis. This combined procedure is simplified as a drainage consolidation method, which is different from the actual conditions of an engineering project. Therefore, it is necessary to further discuss the characteristics of this combined technique.

The electroosmosis permeability will change with time during the process of vacuum preloading combined with electroosmosis. The hydraulic permeability will change greatly due to the continuous consolidation of the soil and discharge of pore water. At the later processing stage of vacuum preloading combined with electroosmosis, the soil is unsaturated; therefore, the physical and mechanical properties of the soil will change to some degree. Thus, due to the abovementioned factors, deviations are observed between the analytical and practical solutions.

Complex chemical reactions will occur in the soil during the process of vacuum preloading combined with electroosmosis. An oxidation reaction will take place at the anode, and a reduction reaction will take place at the cathode. These complex chemical reactions could complicate the two-dimensional consolidation equation. Hence, the two-dimensional consolidation equation is established without considering the occurrence of chemical reactions within the soil in this paper.

The actual distribution of the soil voltage is obtained with the assumption that the methods of vacuum preloading and electroosmosis are initiated and terminated at the same times. If the method of vacuum preloading combined with electroosmosis is used only during the early stage of vacuum preloading, then either electroosmosis alone or the combined method will be used when the soil moisture content drops to a certain value. Consequently, the equation established in this paper may no longer be valid; this situation therefore needs further discussion.

Conclusions

The two-dimensional consolidation equation for the method of vacuum preloading combined with electroosmosis is reformulated based on the actual distribution of the soil voltage. Furthermore, analytical expressions for the excess pore water pressure and the average degree of consolidation are deduced, and the rationality of the consolidation equation is verified by laboratory tests. The analysis demonstrated the following results.

1. The actual distribution of the soil voltage is theoretically derived, and the consolidation equation based on the actual distribution can more realistically reflect the consolidation of soil. Moreover, the consolidation theory of the method of vacuum preloading combined with electroosmosis is further improved, thereby providing a more reasonable reference and guidance for the subsequent application of this combined method in actual construction endeavours.

2. The method of vacuum preloading combined with electroosmosis combines the separate advantages of the electroosmosis and vacuum preloading techniques. The negative excess pore water pressures around the cathode and the anode decrease simultaneously and extends towards their midpoint under the combined action of vacuum preloading and electroosmosis. This finding shows that the method of vacuum preloading combined with electroosmosis can relatively homogenize the strength of the reinforced soil.

3. During the earlier stage of the test, vacuum preloading and electroosmosis play individual roles in the treatment of the soft soil foundation, that is, they cooperate with each other to discharge water from the soil. During the later stage, however, the drainage effect of vacuum preloading is not obvious, and the drainage depends mainly on electroosmosis.

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