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Research Paper

Electro-osmotic consolidation of soil with variable compressibility, hydraulic conductivity and electro-osmosis conductivity

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ABSTRACT

In present study, the non-linear variations of soil compressibility, hydraulic and electro-osmosis conductivities were analyzed through laboratory experiments, and incorporated in a one-dimensional model. The analytical solutions for excess pore water pressure and degree of consolidation were derived, and numerical simulations were performed to verify its effectiveness. The results indicated that both the non-linear variations of hydraulic and electro-osmosis conductivities showed remarkable impacts on the excess pore water pressure and degree of consolidation, especially for soils with relative high compressibility. A further comparison with previous analytical solutions indicated that more accurate predictions could be obtained with the proposed analytical solutions.

1. Introduction

Over the past few decades, there has been a substantial development of infrastructure on soft foundations worldwide. Various treatment methods have been proposed for the improvement of these soft foundations, among which electro-osmotic consolidation has proven to be a promising method, especially for soils with low permeability [1–10]. Unlike the traditional methods such as surcharge and vacuum preloading which dewater soil mass by applying a hydraulic gradient, electro-osmotic consolidation involves pairs of anodes and cathodes installed in the soil mass, through which an electrical field is applied and pore water is driven from the anode to cathode under the electrical gradient. Similar to Darcy's law, the velocity of pore water flow v_e caused by the electrical gradient can be expressed as $k_e \times i_e$, where i_e means electrical gradient and k_e means electro-osmosis conductivity that describes the velocity of pore water under a unit electrical gradient. For different soils, the hydraulic conductivity k_h may change from about 1×10^{-8} cm/s in clay to about 1×10^{-4} cm/s in sand, while k_e is generally in the range of 1×10^{-5} to 1×10^{-4} cm^2/(V s). As a result, a small electrical gradient can balance flows caused by large hydraulic gradient in soft soil with low permeability, and electro-osmosis can be much more efficient than the traditional techniques for soft soil improvement [5, 11–13].

Based on the assumption that the pore water flow resulted from hydraulic gradient and electrical gradient can be linearly superimposed, the governing equation for electro-osmotic consolidation was developed and many analytical solutions were derived based on different conditions to analyze the development of pore water pressure [14–20]. Esrig [14] developed a one-dimensional (1D) model for electro-osmotic consolidation and obtained the analytical solutions for pore water pressure and degree of consolidation considering a permeable cathode and an impermeable anode. Wan and Mitchell [15] further coupled electro-osmotic consolidation with surcharge preloading in a 1D model. Shang [16] and Xu et al. [21] proposed a 2D model in vertical plane to account for the combined action of electro-osmosis with surcharge preloading and vacuum preloading. Su and Wang [22] presented a 2D model in horizontal plane and derived the analytical solutions under different boundary conditions. Li et al. [17] analyzed the average pore water pressure in soils submitted to an axisymmetric electrical field. Wu and Hu [19] developed an axisymmetric model with coupled horizontal and vertical seepage and derived the analytical solution without the equal strain hypothesis. These mathematical analyses have generated significant knowledge pertaining to electro-osmotic consolidation and provided useful formulas for engineering design. However, the electrical and mechanical properties of soil are assumed constant during the derivation of these

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Nomenclature

a, a_0	the coefficient of compressibility and the initial coefficient of compressibility	Q_{ult}	defined variable related to ultimate excess pore water pressure
b	calculating factor related to C_c, M and N	t	time period
A	sectional area of the soil sample	T_v, T_c, T_e	time factors
C_c	compression index	u	excess pore water pressure
C_{v0}	the initial coefficient of consolidation	u_{ult}	ultimate excess pore water pressure
C_0	calculating factor for ultimate excess pore water pressure	U	degree of consolidation
e, e_0	void ratio and initial void ratio	v_z	the pore water flow in the vertical direction
G_n	calculating factors	V	voltage
H	height of the analytical model	V_0	the applied voltage in the electro-osmosis test
I, J	calculating factors	W	ratio between excess pore water pressure and surcharge preloading
k_e, k_{e0}	electro-osmosis conductivity and initial electro-osmosis conductivity	W_{ult}	ratio between ultimate excess pore water pressure and surcharge preloading
k_h, k_{h0}	hydraulic conductivity and initial hydraulic conductivity	Z	ratio between vertical position and height of the model
L	length of the soil sample	α, θ	calculating factors
M, N	factors describing the change in hydraulic and electro-osmosis conductivities resulted from the change in void ratio	β	calculating factor related to surcharge preloading and initial effective stress
		γ_w	unit weights of water and saturated soil
		σ', σ_0	effective stress and initial effective stress
p_0	surcharge preloading	ε	the weighted factor
q	volume of the discharged water due to electro-osmosis	ξ_n	solution for $\tan(\xi/2) = \xi/\theta$, where n equals 1,2,3……
Q	defined variable related to the excess pore water pressure	λ_n	equals $(\xi_n{}^2 + \theta^2)/4$

analytical solutions. In fact, the flow of pore water from anode to cathode during electro-osmosis causes the decrease in water content and void ratio of the treated soil, and leads to non-linear variations in soil properties such as compressibility, hydraulic conductivity and electro-osmosis conductivity [1,4,5,7,13,23–28]. Such variations would inevitably affect the development of pore water pressure during electro-osmotic consolidation, and the predictions from the existing analytical solutions with constant soil properties would be inaccurate.

Although being ignored in the analytical solutions for electro-osmotic consolidation, the non-linear variations of soil compressibility and hydraulic conductivity have already been investigated in many consolidation theories [29–38]. Davis and Raymond [29] derived the analytical solution for pore water pressure with the assumption of non-linear compressibility and constant coefficient of consolidation. Poskitt [31] further coupled the relationships between void ratio (e) and effective stress (σ'), hydraulic conductivity (k_h) into a vertical consolidation model. Lekha et al. [33] presented closed form analytical solutions for the pore water pressure and degree of consolidation for the particular cases of $e - \log(\sigma')$ and $e - \log(k_h)$ responses. In these studies, the relationships of $e - \log(\sigma')$ and $e - \log(k_h)$ were developed and incorporated to account for the non-linear variations of soil compressibility and permeability.

Compared to the traditional consolidation problem, electro-osmotic consolidation involves not only the non-linear variations of soil compressibility and permeability but also the change in electro-osmosis conductivity. In this study, a series of experiments were performed to investigate the variations of hydraulic and electro-osmosis conductivities during electro-osmotic consolidation. Afterwards, the relationships between the hydraulic conductivity, electro-osmosis conductivity and void ratio were developed based on the experiment results, and further incorporated into a 1D model for electro-osmotic consolidation together with the conventional $e - \log(\sigma')$ response. The analytical solutions for excess pore water pressure and degree of consolidation were derived and compared with that from Wan and Mitchell (1976) to investigate the effects of the non-linear variations of soil properties.

2. Experimental study

A kaolinite from Jiangsu Province, China was used to conduct permeability and electro-osmosis tests. The basic properties and chemical composition of the kaolinite were listed in Table 1. The as-received kaolinite was first oven dried, then mixed with water at a water content of 10% and compacted into the test devices in five layers according to the pre-determined void ratio in the range of 1.373–0.919, and finally saturated under a vacuum.

The hydraulic conductivities of the kaolinite samples were monitored with the falling head permeability test, and the electro-osmosis conductivities were measured using a self-designed apparatus 90 mm in diameter and 400 mm in height as shown in Fig. 1. The anode platen was placed on the bottom of the kaolinite sample, while the porous cathode platen on the top, allowing the drainage of pore water into a graduated cylinder. In order to eliminate the effect of hydraulic gradient, the bottom of the kaolinite sample was connected to a water reservoir with a

Table 1
Geotechnical properties and chemical composition of the kaolinite.

Geotechnical property	Value
Initial water content, w_0 (%)	1.31
Liquid limit, w_L (%)	58
Plastic limit, w_p (%)	23
Plasticity index, I_p (%)	35
Specific gravity, G_s	2.61
Chemical composition	2.0
SiO_2	50
Al_2O_3	35
Fe_2O_3	3.2
$K_2O + Na_2O$	4.2