Investigation of Excess Pore Water Pressure in Cone Penetration Test in Saturated Clayey Soils under Undrained Condition

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ABSTRACT

The widespread use of the cone penetration test in geotechnical engineering, due to its quick identification of soil layers and properties, has led to the development of various analytical methods for interpreting this test. Monitoring excess pore water pressure during the piezocone penetration test can be crucial for assessing the properties and engineering parameters of clayey soils. The initial stresses in the ground and the coefficient of lateral earth pressure at rest, K_0, are important parameters needed for the design and analysis of various geotechnical problems such as piles, and slope stabilities. Due to the limited research on clayey soils, the significance of understanding their behavior, and the limitations of laboratory experiments, this study investigates soil behavior via numerical modeling of cone penetration tests in saturated clay with undrained conditions. In this study, the effect of the coefficient of lateral earth pressure and initial effective vertical stresses on pore water pressure has been investigated. Additionally, the correlations between excess pore water pressures at points u_2 and u_1, as well as u_2 and u_3, have been outlined. Modified Cam-Clay constitutive model was employed in all numerical analyses using FLAC2D software. The validation of proposed relationships was also addressed using the database of field tests available in the literature provided by different researchers. The obtained results indicated that as each parameter of lateral pressure coefficient and vertical effective stress increased, the excess pore water pressure also increased at all three locations where pore water pressure is measured.

KEYWORDS

Numerical modeling, Piezocone penetration test, Vertical effective stress, Coefficient of lateral earth pressure, Modified Cam - Clay model

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1. Introduction

The Cone Penetration Test (CPT), involving the continuous penetration of a cylindrical tool with a conical tip into the ground, has gained widespread popularity worldwide due to its efficiency and cost-effectiveness. This test not only measures the resistance of the cone tip and the friction sleeve but also allows for the measurement of pore water pressure. Pore water pressure sensors are located at the cone shoulder (u_2), at the mid face of the cone (u_1), and behind the friction sleeve (u_3) [1]. For all soil types, particularly those with high over-consolidation ratio, the maximum pore water pressure typically occurs at u_1 location, gradually decreasing towards u_3 [2]. Several factors influence pore water pressures. Important factors include the coefficient off lateral pressure (K_0), over-consolidation ratio, and initial stresses. The initial stress condition of the soil and the coefficient of lateral earth pressure are crucial for the design of various geotechnical problems such as retaining walls, piles, and slope stabilities [3]. In soils with a high over-consolidation ratio, due to the dilative soil behavior, there is a tendency to suction along the friction sleeve, leading to a negative excess pore water pressure (EPWP) in the soil [4]. Consequently, as the over-consolidation ratio increases, the EPWP decreases along the friction sleeve. At the location u_1, the EPWP (Δu_1) is always positive; However, behind the cone shoulder, this EPWP (Δu_2) can be either positive or negative based on the level of over-consolidation ratio, sensitivity, and the soil disturbance.Numerous studies have been carried out in this field, including the works of Sully et al. (1991), Moug et al. (2019), as well as Mashinchian and Ahmadi (2024) [5-7]. The number of research on the friction sleeve is generally less than the studies on the mid face of the cone, which can be attributed to the fact that the u_3 sensor is not commonly installed behind the friction sleeve of the cone. In this research, firstly, the effect of two parameters K_0 and σ'_{v0} on pore water pressure was investigated, and then a relationship between EPWP at u_1, u_2, and u_3 was presented according to the aforementioned parameters.

2. Methodology

Numerical simulation of cone penetration testing in saturated undrained clayey soil has been performed, employing finite difference method. FLAC 2D software was used to solve equations and simulate the conditions under axial symmetry [8]. In this model, the standard piezocone has a cross-section of 10 cm² and an apex angle of 60°. Soil dimensions, cone radius, meshing, boundary conditions, and applied stresses are illustrated in Figure 1. In this research, to simulate the behavior of clayey soils, the Modified Cam-Clay Model was utilized. Table 1 outlines the soil properties of studied clayey soil. To investigate the effect of σ'_{v0} and K_0 on the EPWP in Boston clay, five σ'_{v0} (50, 100, 150, 200, and 300 kPa) and four K_0 (0.49, 0.73, 0.9, and 1) were examined.

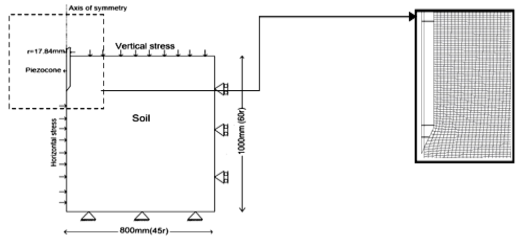

Figure 1: Boundary conditions and initial meshing of the finite difference model.

Table 2: Modified Cam-Clay parameters of Boston Blue Clay (BBC) soil.

soil	κ	λ	v_λ	M	σ'_{v0} (kPa)	OCR	Reference
Boston Blue Clay (BBC)	0.03	0.15	2.83	1.2	100	2.2	Moug et al. (2019)

3. Results and Discussion

To examine the effect of the K_0 parameter on the EPWP developed in the cone penetration test for Boston Blue clay, four different K_0 values were considered under a constant σ'_{v0} of 100 kPa. Subsequently, the EPWP at three locations u_1, u_2, and u_3 has been monitored. Based on the results, as the K_0 value increases, the EPWP increases at locations u_1, u_2, and u_3. To study how the σ'_{v0} affects the EPWP, five different σ'_{v0} values of were considered under a constant K_0 value of 0.73. The results indicated that as σ'_{v0} value increases, under the specified K_0 value, EPWP increases at locations u_1, u_2, and u_3. The investigation of the EPWP along the friction sleeve between u_2 and u_3 for two K_0 values and varying σ'_{v0} values at K_0=0.73 are depicted in Figure 2. In this figure, it is evident that as K_0 increases, the ratio of $(\Delta u_z)/(\Delta u_2)$ along the friction sleeve reduces more rapidly. This trend can be attributed to the dilative behavior of the soil. Based on the results obtained, a formula can be derived for the values of EPWP along the friction sleeve via Eq. (1). In this equation, α and β, as constant and dimensionless parameters, are calculated individually for each specific location using Eq (2) and (3) derived by nonlinear regression analysis.

$$\frac{\Delta u_z}{\Delta u_2} = \exp\left(\left(\frac{\beta^{0.5}}{-\alpha} \times \frac{z}{0.15}\right)\right) \quad (1)$$

$$\beta = \frac{K_0^{2.5}}{I_r^{0.7}} \quad (2)$$

$$K_0 < 1 \rightarrow \alpha = \frac{K_0}{(\ln(\frac{q_t}{\sigma'_{v_0}}))^{1.5}}$$
$$K_0 \geq 1 \rightarrow \alpha = \frac{K_0^{\,2} - 0.5}{\ln(\frac{q_t}{\sigma'_{v_0}})} \tag{3}$$

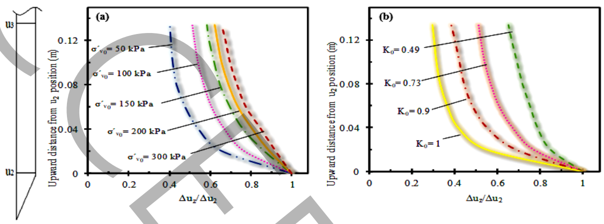

Figure 2: Distribution of EPWP along the friction sleeve of the piezocone; (a) For different vertical effective stresses, (b) For different lateral earth pressure coefficients.

The analysis of the generated EPWP was further explored along the cone face along the distance between u_2 to u_1 under two scenarios with varying values of K_0 and different σ'_{v0} values of at K_0 =0.73, as illustrated in the Figure 3. In this figure, the downward movement from u_2 to u_1 is regarded as positive. When the cone penetrates into the soil, the EPWP along the cone tip initially increases, then decreases. As the piezocone tip penetrates into the soil, stresses increase until the diameter of the penetrated soil reaches the cone diameter, after which the stresses becomes constant. This gradual increase in stress until reaching a constant stress leads to a gradual increase in the EPWP. The zones near the piezocone shoulder exhibits the highest ratio of $(\Delta u_z)/(\Delta u_2)$. Eq. (4) was proposed for the EPWP ratio along the cone tip. In this equation, α is a dimensionless constant parameter determined at each location based on Eq. (5) derived from nonlinear regression analysis.

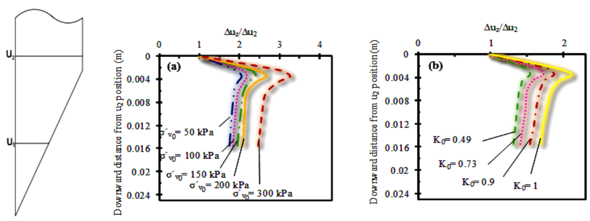

Figure 3: Distribution of EPWP along the piezocone face; (a) For different vertical effective stresses, (b) For different lateral earth pressure coefficients.

$$\frac{\Delta u_z}{\Delta u_2} = \exp(\frac{z^{0.1}}{\alpha}) - \left(\frac{z}{0.02}\right) \tag{4}$$

$$K_0 < 0.8 \rightarrow \alpha = \left(\frac{(\frac{q_t}{\sigma'_{v_0}}) \times I_r}{800}\right)^{K_0^{\,3}}$$
$$K_0 \geq 0.8 \rightarrow \alpha = \frac{1 + K_0}{\ln(\frac{q_t}{\sigma'_{v_0}})} \tag{5}$$

4. Conclusion

In this research, through numerical modeling of cone penetration tests in saturated clayey soils under undrained conditions, it was observed that:

1. The increase of K_0 value, leading to an increase in EPWP during cone penetration at u_1, u_2, and u_3. For constant σ'_{v0} values, with the increase of the K_0 values, the ratio of $(\Delta u_z)/(\Delta u_2)$ increases along the cone face. However, along the friction sleeve, increasing the K_0 leads to a decrease in the ratio of $(\Delta u_z)/(\Delta u_2)$. 2. The initial σ'_{v0} value has an effect on the value of EPWP and causes an increase in the pore water pressure during the penetration of the cone at location u_1, u_2, and u_3. At a constant K_0 value, with the increase of the σ'_{v0} values, the ratio of $(\Delta u_z)/(\Delta u_2)$ increases along the cone face and the friction sleeve.

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