XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Numerical analysis of the effect of penetration rate in piezocone tests on silty soils

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Abstract. Partial drainage is a relevant effect in piezocone tests (CPTu) performed on geomaterials with intermediate permeability, such as silts and mine tailings. However, the penetration rates that cause partial drainage vary for each material. Thus, to investigate the effects of the cone penetration rate on different geotechnical properties, numerical simulations of cavity expansion were performed. The Cam-Clay model was used, and the parameters of strength (M), stiffness (κ and λ), and permeability (k) were varied for different cone penetration rates. The material studied was silt from the Yellow River Delta (China) through the tests performed in centrifuges by several authors. With the results of the numerical simulations, it was possible to obtain the theoretical drainage curves of the material, which indicate the penetration velocities that trigger partial drainage. Sensitivity analysis demonstrated the large effect of the friction coefficient on the drainage curve, the increase in soil stiffness leads to a decrease in penetration rates and the alteration in the material permeability does not change the magnitude of the resistance and excess pore pressure generated. The comparison with experimental centrifuge results indicated good agreement of the numerical analysis.

Keywords: cavity expansion, finite element, cone penetration rate.

1 Introduction

Piezocone penetration tests (CPTu) are in situ tests widely used in geotechnical investigations. From the test results, soil strength parameters can be obtained, such as the friction angle (φ) in sands and the undrained shear strength (Su) of clays. This is because, at the standard penetration rate (20 ± 5 mm/s), sandy soils have a drained behavior, while cohesive soils have an undrained behavior. On silty soils, however, partial drainage may occur for this penetration rate, which can lead to incorrect test results and interpretations (Salgado et al. [1]; DeJong and Randolph [2]; DeJong et al., [3]; Salgado and Prezzi,[4]; Dienstmann et al. [5]; Schnaid et al. [6]).

The effect of the penetration rate of CPTu tests on intermediate soils has been investigated in field and aiming for a more rigorous boundary conditions in laboratory through centrifuge and calibration chamber tests. Site and laboratory investigation set can be complemented with numerical modeling, aiming to rationalize the interpretation. In this sense, cavity expansions are accepted simplified solutions usually used in geomechanics to represent inclusions due in situ tests and pile installation. In the literature, solutions for cylindrical (Silva [7]; Jaeger [8]) and spherical (Xu and Lehane [9]; Lehane et al. [10]; Tolooiyan and Gavin [11]) geometries are reported.

Considering a cylindrical expansion, the tip resistance (q_c) mobilized in CPTu test can be associated with effective radial stress and mobilized pore pressure by the equation 1. A proposal similar to Rohani and Baladi [12], used by Silva et al. [13] and LeBlanc and Randolph [14]:

$$q_c = \sigma_r' \frac{1+\tan\delta/\tan\alpha}{1-\tan\delta\tan\alpha} + u \quad (1)$$

where δ is the interface friction angle; α is the angle between the face of the conical tip and the vertical line; σ'_r is the radial effective stress; and u is the pore pressure. In the present paper parameter δ was assumed to be the same as the constant volume friction angle (φ_{cv}) of the soils.

Expression 1 can be used to establish theoretical drainage characteristic curves, a relation of normalized velocity V (V_v or V_h) and Q considering expressions:

$$Q = \frac{q_c - \sigma_{v0}}{\sigma'_{v0}} \tag{2}$$

$$V_v = \frac{v \cdot d}{c_v} \quad or \quad V_h = \frac{v \cdot d}{c_h} \tag{3}$$

where v is the penetration rate; d is the probe diameter; c_v is the vertical consolidation coefficient; and c_h is the soil horizontal consolidation coefficient. For isotropic materials, $c_v = c_h$.

The present paper describes the application of a classical unidimensional cavity expansion model to investigate the influence of strength (M), stiffness (κ and λ) and permeability (k) parameters during variable expansion rates. Additionally, CPTu results and characteristic properties of an intermediate soils (Yellow River Delta Silt) were used to perform a set of numerical analysis to define theoretical characteristic drainage curves that were directly confronted with field data.

2 Cavity Expansion

The cylindrical cavity expansion was simulated in Abaqus software through an axisymmetric model with a Clay Plasticity constitutive model and CAX8RP-type elements: an 8-node axisymmetric quadrilateral, biquadratic displacement, bilinear pore pressure and reduced integration. In this model (Fig. 1), an initial cavity of radius R is expanded by applying a controlled radial displacement (ζ_r), up to a value of 25% R. The radial extension of 50 R proved sufficient to not generate a boundary effect. The boundary conditions were roller support (u_z=0) on the top and bottom faces and roller support (u_x=0) on the right face. The initial stresses and pore pressures were applied through a predefined field, proposed by Dienstmann [15]:

$$u_0 = u_{max,0} \frac{1 - a/r + (a/R)\ln(a/r)}{1 - a/R + (a/R)\ln(a/R)} \quad para\ R \leq r \leq a \tag{4}$$

where $u_{max,0}$ is the maximum initial pore pressure; a is the pore pressure influence radius; R is the initial cylinder radius; and r is the radial distance.

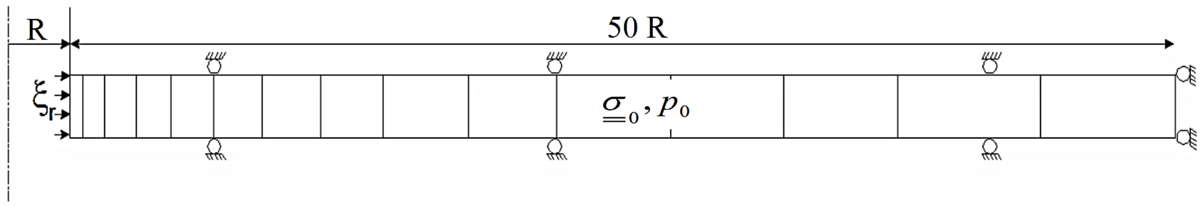

Figure 1. Finite-element mesh detail, adapted from Dienstmann [15].

3 Sensitivity analysis

A sensitivity analysis was performed to characterize the influence of the friction coefficient (M), compression and recompression index (λ and κ) and permeability coefficient (k) over stresses generated by the cavity expansion. The parameters used in the analyses are presented in Tab. 1. A total of 54 simulations were run, divided into 3 groups, to separately evaluate the effect of the parameter under study. From the sensitivity analysis results, normalized drainage curves (Q - V_h and $\Delta u/\sigma'_{v0}$) were drawn for each of the 3 groups.

Figure 2 shows the effect of the friction coefficient (M), which, as expected, causes an increase in the cone resistance and excess pore pressure generated. The compression (λ) and recompression (κ) index variation, presented in Fig. 3, indicated that the stiffer the material (lower value of λ and κ), the greater the strength mobilized. In the normalized excess pore pressure plot, a decrease in the penetration rates that define partial drainage is observed with increasing stiffness. Figure 4 shows the curves generated by changing the soil permeability coefficient (k). Note that the three curves complement each other since the increase in this coefficient is inversely linear to the normalized penetration rate; thus, the more pervious the soil is, the lower the rate obtained. The drainage curves, however, are identical to the intermediate cases (M 1.20, κ 0.006 and λ 0.037) of Figs. 2 and 3.

Table 1. Parameters used in sensitivity analysis

Parameter	**Value**	**Unit**
p_{c0}	200	kPa
p'_0	100	kPa
$u_{max,0}$	p_{c0} (1+M/3)/2	kPa
p_0	$p'_0+u_{max,0}$	kPa
v	0.0001; 0.001; 0.01; 0.1; 1; 10	m/s
M	0.77; 1.20; 1.64	-
κ	0.004; 0.006; 0.008	-
λ	0.025; 0.037; 0.050	-
k	3E-2; 3E-4; 3E-6	m/s
ν	0.28	-
e_0	0.74	-
R	0.005	m
a	25 R	m

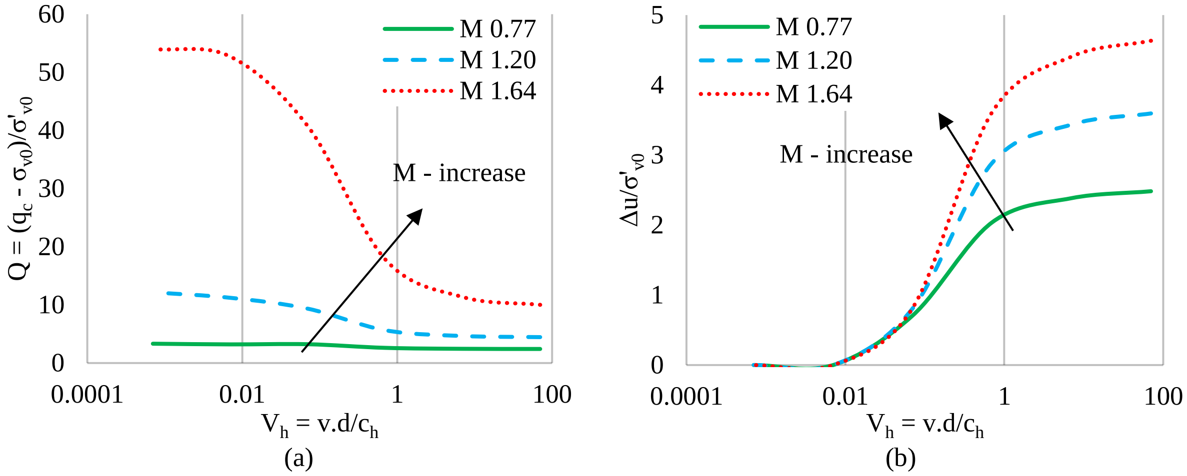

Figure 2. Effect of the friction coefficient (M): (a) Q - V_h; (b) $\Delta u/\sigma'_{v0}$ - V_h.

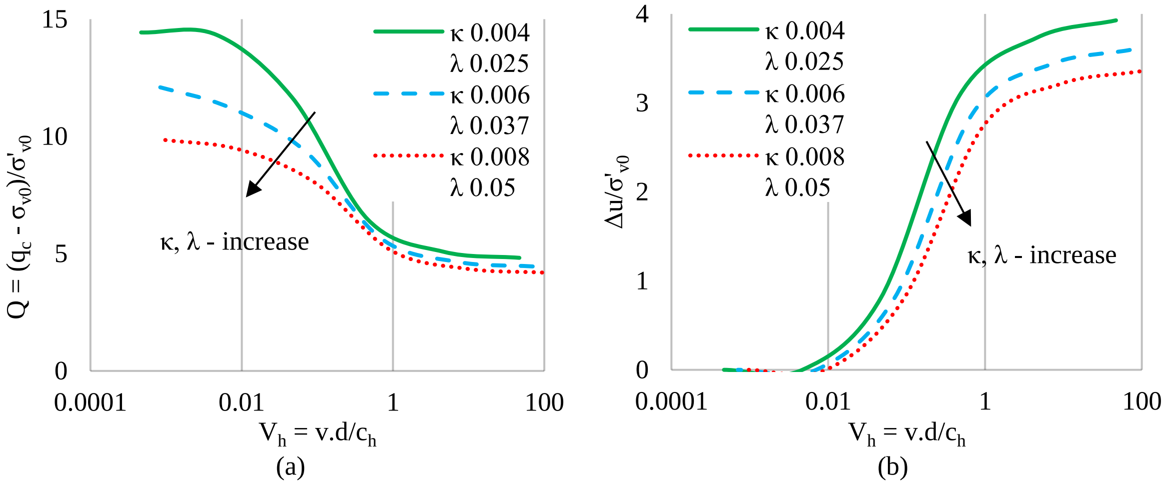

Figure 3. Effect of compression index (λ) and recompression index (κ): (a) Q - V_h; (b) $\Delta u/\sigma'_{v0}$ - V_h.

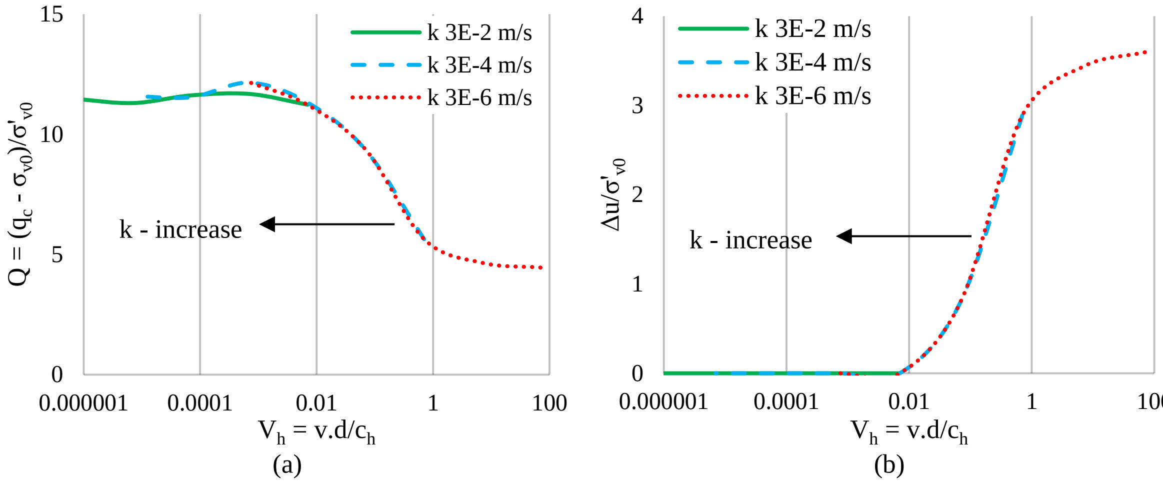

Figure 4. Effect of permeability coefficient (k): (a) Q - V_h; (b) $\Delta u/\sigma'_{v0}$ - V_h.

4 Yellow River Delta Silt

The Yellow River Delta (YRD) is located in northern Shandong Province (China) and is formed by rapidly deposited sediments, which are mainly composed of silty soils (Feng et al. [16]; Jia et al. [17]; Zhang Y. et al. [18]). The parameters of the YRD silt used in the numerical analyses were obtained from Zhang Y. et al. [18] and Zhang J. et al. [19]. Figure 5 shows the consolidation-undrained triaxial shear test (CU) results of the YRD silt and kaolin-YRD silt mixtures. The mixtures containing 20% and 30% clay are notated as 20% C and 30% C, and the preparation process of each test is stated as follows: slurry deposition (DS), moist tamping (MT) and dry deposition (DD). The results vary greatly depending on the different preparation methods used.

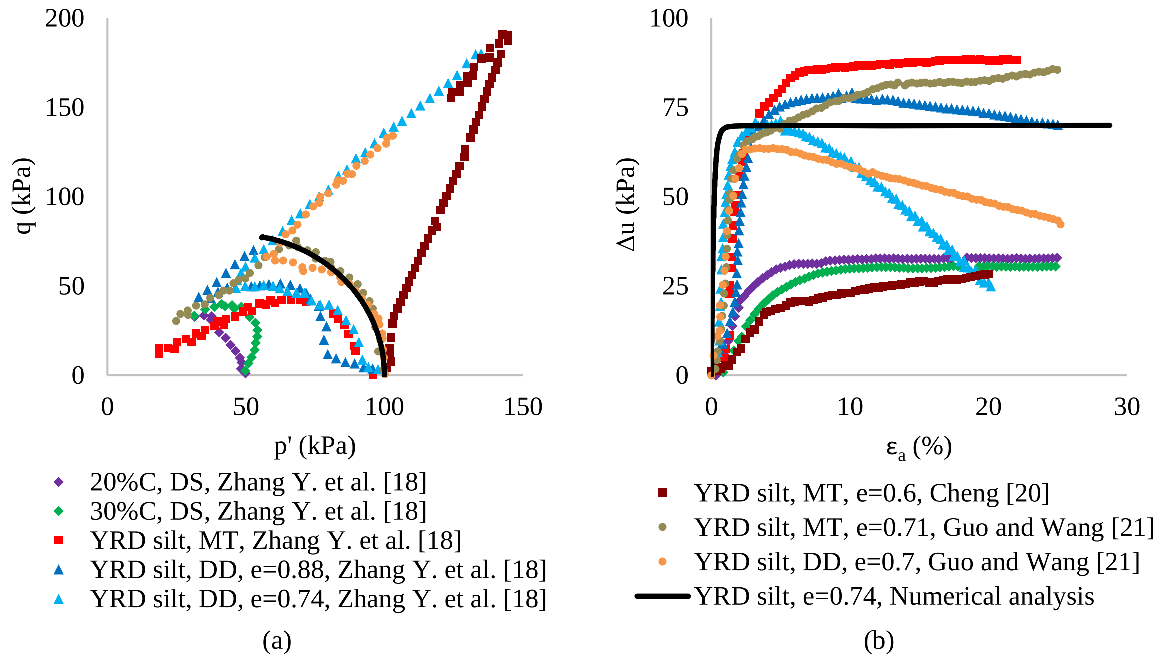

Figure 5. Consolidation-undrained triaxial shear test results for YRD silt and kaolin-YRD silt mixtures: (a) stress paths in the q-p′ space; (b) excess pore pressure-strain responses (Δu-ε_a).

Aiming to verify the adequacy of the Clay Plasticity model (Abaqus) to the YRD silt, a consolidated-undrained triaxial test was modeled in the finite element software Abaqus, considering geotechnical parameters provided in Zhang J. et al. [19], Tab. 2.

Table 2. Parameters used in consolidation-undrained triaxial simulation

Parameter	Value	Unit
p_{c0}	100	kPa
p'_0	100	kPa
e_0	0.74	-
γ	20.0	kN/m^3
γ_w	9.81	kN/m^3
v	0.0000125	m/s
M	1.38	-
κ	0.006	-
λ	0.037	-
k	3E-6	m/s
ν	0.28	-

The model consists of a single 2.5x2.5 cm element, CAX8R-type. The boundary conditions were symmetry axis (u_x=0) on the left face, roller support (u_z=0) on the bottom face, and zero pore pressure on the top face during the consolidation step. The result of the numerical analysis is also plotted in Fig. 5, which shows a fully nondrained behavior, close to the Guo and Wang [21] curves, and generates an excess pore pressure similar to most tests.

Then, a cylindrical cavity expansion analysis was performed for the Yellow River Delta silt parameters (Tab. 3). The normalized drainage curve was compared with centrifuge test results at 1 g for YRD silt samples (Zhang J. et al. [18]) and at 100 g and 1 g for 25% kaolin-YRD silt mixture samples (Jaeger et al. [22] and Kim et al. [23], respectively).

Table 3. Parameters used in cavity expansion simulation

Parameter	Value	Unit
p_{c0}	200	kPa
p'_0	100	kPa
$u_{max,0}$	p_{c0} (1+M/3)/2	kPa
p_0	$p'_0+u_{max,0}$	kPa
v	0.0001; 0.001; 0.01; 0.1; 1; 10	m/s
M	1.38	-
κ	0.006	-
λ	0.037	-
k	3E-6	m/s
ν	0.28	-
e_0	0.74	-
R	0.005	m
a	25 R	m

Figure 6 presents the comparison between experimental and numerical results, in which a good agreement can be seen on the drained branch of the normalized cone resistance curve. For the undrained branch, however, the experimental results exhibited a lower resistance (about 50% of numerical analysis value). Lastly, the excess pore pressure curve displayed an excellent agreement with the centrifuge results.

5 Conclusions

The impact of the piezocone penetration rate on intermediate soils was analyzed using a cylindrical cavity expansion model of the Yellow River Delta Silt. The Clay Plasticity constitutive model exhibited good agreement with consolidated undrained triaxial tests.

Sensitivity analysis demonstrated the large effect of the friction coefficient on the drainage curve, especially on the drained branch. In addition, it was possible to verify that the increase in soil stiffness leads to a decrease in penetration rates that indicate partial drainage. Additionally, that alteration in the material permeability does not change the magnitude of the resistance and excess pore pressure obtained only shifts the drainage curve to the left with the increase in permeability.

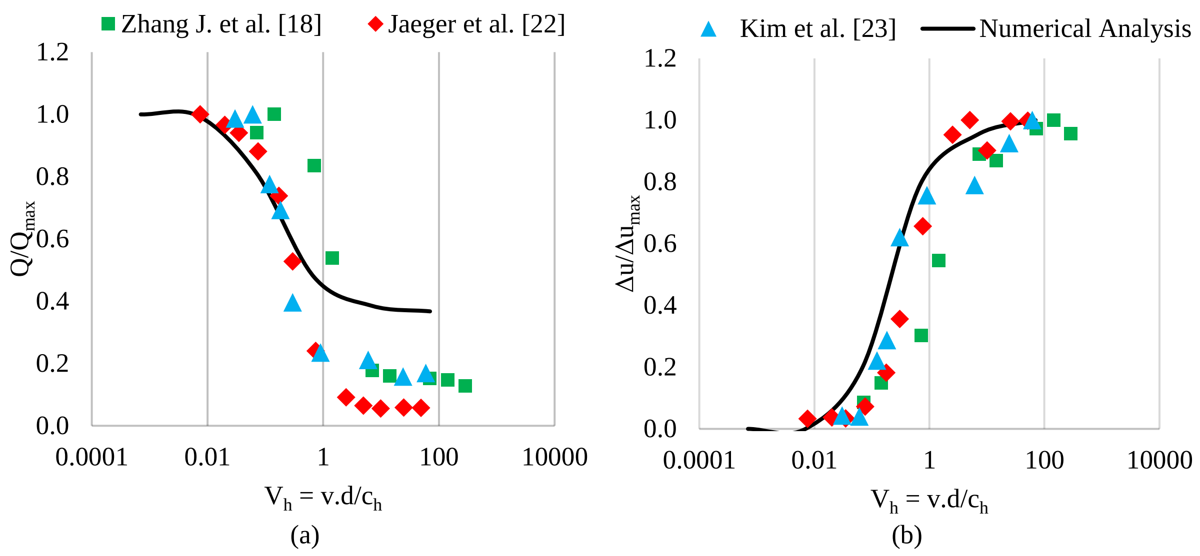

Figure 6. Comparison of penetration test results of YRD silt and kaolin-YRD silt mixtures with the numerical analysis: (a) Q/Q_{max} - V_h; (b) $\Delta u/\Delta u_{max}$ - V_h.

Finally, the comparison with experimental centrifuge results indicated good agreement of the numerical analysis only in the drained branch of the normalized cone resistance curves (Q/Q_{max}), with the strength in the undrained branch being overestimated. However, the normalized excess pore pressure curve ($\Delta u/\Delta u_{max}$) showed excellent agreement with the experimental results.

It is noteworthy, however, that with the results of the numerical simulations, it is possible to obtain the theoretical drainage curves of the material, which indicate the penetration velocities that trigger partial drainage. The application of understanding the effects of piezocone penetration rate effects under partially drained conditions occurs through technical support for geotechnical risk assessment in works that involve materials with silty characteristics.

Acknowledgments. This paper was carried out with the support of the Santa Catarina Research Foundation (FAPESC). The authors also thank the Department of Civil Engineering and the PostGraduate Program in Civil Engineering (PPGEC) of the Federal University of Santa Catarina (UFSC) for their assistance in the elaboration of this study.

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