Variable penetration rate CPT in an intermediate soil

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ABSTRACT: Soil behavior during CPT is controlled by the drainage conditions and deformation rate effects of the soil being tested. The behavior of most intermediate soils (e.g silty clays, clayey sands) during CPT is neither drained nor undrained since their permeabilities fall between those of sand and clay. Thus, neither drained nor undrained soil properties can be reliably estimated due to the partially drained conditions of the test. The results of variable penetration rate CPT in an intermediate soil comprising 75% sand and 25% kaolin performed during a centrifuge experiment are presented and compared to previously published results. The effects of varying the penetration rate on normalized CPT parameters as well as on the conventional soil classification chart are presented.

1 INTRODUCTION

Current engineering practices for the characterization of and design with coarse-grained materials (e.g. sands) and fine-grained materials (e.g. clays and plastic-silts) are well established. However, intermediate soils such as silts and clayey-sands (with low plasticity) are typically more problematic. Drained conditions are assumed to exist in sands and undrained conditions are assumed to exist in clays during cone penetration at the ASTM standard penetration rate of 2.0 cm/sec. Cone penetration testing (CPT) at 2.0 cm/sec in intermediate soils may be neither drained nor undrained since their permeabilities fall between those of sand and clay. Therefore, no current method to estimate drained or undrained material properties from CPT can be applied reliably to intermediate soils whose response to conventional CPT is partially drained.

The results of variable penetration rate CPT in an intermediate soil comprised of 75% sand and 25% kaolin performed during a centrifuge experiment are presented and compared to previously published results. Effects of penetration rate on penetration resistance and the pore pressure measurements are explored and parameters for characterizing the effects of varying the penetration rate on intermediate soil response are suggested. Current CPT soil behavior type characterization charts are also explored to see how penetration rate affects their use.

2 CENTRIFUGE EXPERIMENT

2.1 *Equipment*

The centrifuge experiment was performed using a 1.8 m radius beam centrifuge at the University of Western Australia, Perth. The centrifuge strongbox dimensions are 650 x 390 mm in plan. A 10 mm diameter miniature piezocone with pore pressure measurements taken at the u_2 position (at the cone shoulder) was used in the experiment. Desaturation of the piezocone prior to insertion was prevented by keeping the probe in water during consolidation of the sample in the centrifuge.

2.2 *Material and Material Properties*

A 75% sand and 25% kaolin clayey-sand mixture was used to create an intermediate soil for variable penetration rate testing. The soil was prepared from a slurry condition (water content equal to 1.75 times the liquid limit) and mixed using a concrete mixer with air suction to minimize the amount of air in the soil. The soil was lightly overconsolidated prior to spinning using a press to apply 20 kPa to the surface of the sample to minimize segregation of the sand and clay particles. The strongbox was then placed onto the centrifuge arm and allowed to consolidate for 48 hours at an acceleration of 100 g. Consolidation of the sample was verified using an array of pore pressure measurements along the depth of the box. Supplemental laboratory testing measurements were performed on similarly prepared samples to determine the critical state friction angle (ϕ'_{cs} = 28°), plasticity index (PI = 9.5), grain size distribution, and consolidation characteristics. The following correlation between vertical consolidation stress and the vertical coefficient of consolidation was found to fit the data well:

$$c_v = 19(\sigma'_v / p_a)^{0.83}\ \mathrm{m}^2 / yr = 0.61(\sigma'_v / p_a)^{0.83}\ \mathrm{mm}^2 / s \qquad (1)$$

where σ'_v is the vertical effective stress, p_a is atmospheric pressure and c_v is the vertical coefficient of consolidation. The vertical effective stress within the centrifuge model was estimated using density samples taken immediately after spinning (γ' = 11.0 to 11.7 kN/m^3). The vertical coefficient of consolidation was then estimated using the correlation provided in (1).

2.3 *Testing Program*

Fifteen piezocone penetration tests were performed during spinning at an acceleration of 100 g. Constant and variable penetration rate cone penetration tests were performed to provide reference tests for evaluating rate effects.

Cone penetration rates were varied between 0.003 mm/sec to 3.0 mm/sec over approximately the same depth ranges for each of the profiles. Incremental penetration of 60 to 80 mm (6 to 8 cone diameters) was used for each penetration rate to ensure that steady conditions developed (e.g. where penetration resistance and pore pressure become steady). Two twitch tests, where the penetration rate was successively halved after 1 to 2 cone diameters of penetration, were also performed (House et al., 2001).

3 ANALYSIS OF RESULTS

3.1 *Cone Penetration Testing Profiles*

Cone penetration tests 5, 6, 7, and 9 illustrate the effects of variable penetration rate testing on penetration resistance, pore pressure, and drainage conditions (Fig. 1). CPT 9 was pushed rapidly at a constant rate of 3.0 mm/sec and is included as an undrained reference profile for the other tests. The hydrostatic pressure distribution is also included as a drained reference (i.e. zero excess pore pressure).

CPTs 5, 6, and 7 have a penetration rate of 1.0 mm/sec initially. Pore pressures in each of these tests were approximately equal up to a depth of 40 mm, indicating that penetration rates above 1.0 mm/sec were all undrained. The penetration rates of CPTs 5, 6, and 7 were then decreased to 0.5 mm/sec, 0.3 mm/sec, and 0.2 mm/sec, respectively. The pore pressure and penetration resistance measurements remained approximately equal to the undrained reference (CPT 9), indicating that 0.2 mm/sec penetration rate also remained undrained. At 110 mm depth, penetration rates were decreased to 0.02 mm/sec, 0.03 mm/sec, and 0.06 mm/sec, respectively. Here, the pore pressures of CPTs 5, 6, and 7 decreased and reached stable, partially drained conditions after about four probe-diameters of penetration. At the slowest rate (CPT 5), nearly drained conditions were achieved. Penetration resistance increased significantly due to the increase in effective stress around the probe (due to the decrease in excess pore pressure).

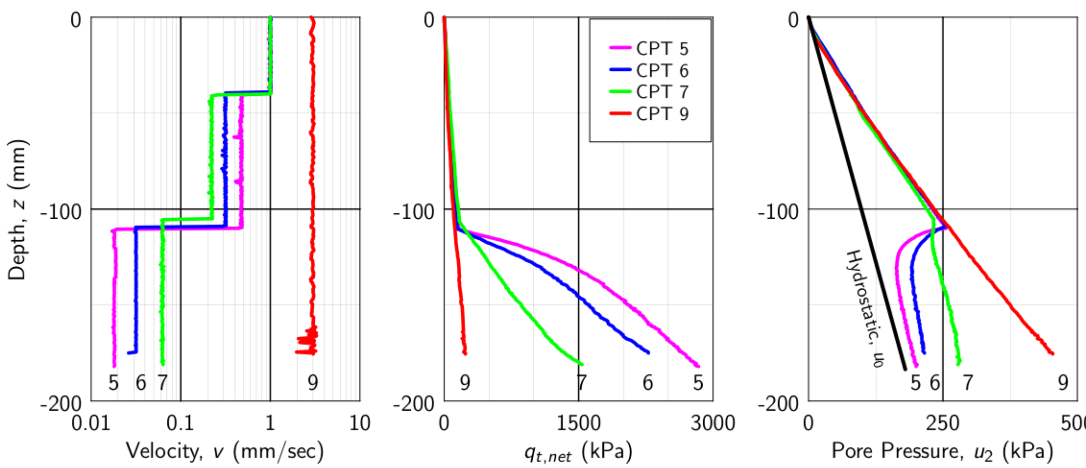

Figure 1: Variable penetration rate cone penetration testing profiles in 75% sand, 25% kaolin mixture.

3.2 *Data Selection*

Data points were chosen from multiple depths and varying penetration rates in the cone penetration tests at points where penetration was determined to be steady, meaning that there were no sudden changes in penetration resistance or pore pressure trends. Additionally, points were not used if they were within four probe diameters (40 mm) of the surface or bottom of the container to eliminate boundary effects and ensure steady penetration of the data selected.

3.3 *Normalized Velocity*

Dimensionless parameters are used to compare the cone penetration measurements from multiple penetration rates, depths, soils, and initial conditions. Finnie & Randolph (1994) suggested a dimensionless velocity of the form:

$$V = \frac{vd}{c_v} \tag{2}$$

where v is the penetration rate (mm/sec); d is the cone diameter (10 mm in model scale); and c_v is the vertical coefficient of consolidation (mm^2/sec). This form of dimensionless velocity accounts for differences in velocity, soil compressibility, probe size, material type, void ratio, and stress conditions.

3.4 *Effect of Penetration Rate on Penetration Resistance*

The variation of normalized penetration resistance (Q) with normalized velocity (V) for the sand-kaolin mixture led to several interesting observations. Firstly, Q monotonically decreased as normalized velocity (V) increased from 0.01 to 160 (Fig. 2). Randolph (2004) showed that viscous effects begin to increase penetration resistance for V > 100 in kaolin samples. However, these effects were absent from the present sand-kaolin experimental data.

Secondly, the dataset shows two clearly stabilized regions of normalized penetration resistances at the extremes of this range, which are believed to correspond to drained penetration for V < 0.01 and undrained penetration for V > 20. Finnie & Randolph (1994) suggest that drained conditions exist at normalized velocity V < 0.01 and undrained conditions exist for V > 30. Randolph (2004) and Schneider et al. (2007) suggest that undrained conditions exist for V > 100 in normally consolidated and lightly overconsolidated samples.

Lastly, the ratio of $Q_{drained}$ to $Q_{undrained}$ is approximately 17, which is much larger than what has been seen in previous literature on variable penetration rate cone penetration testing. Results from Schneider et al. (2007) for cone penetration tests in normally consolidated kaolin (NC Kaolin, OCR = 1.0, PI = 34), lightly overconsolidated silica flour-bentonite (LOC SFB, OCR = 1.5 to 2.0, PI = 12 to 14), overconsolidated kaolin (OC kaolin, OCR = 5.0 to 6.5), and an overconsolidated silica flour-bentonite (HOC SFB, OCR = 5.0 to 6.5) have ratios of drained to undrained (or minimum) normalized penetration resistance between 2 and 3. Finnie and Randolph (1994) have shown similar results for shallow foundations, where ratios of drained to undrained dimensionless bearing modulus were much more dramatic in calcareous silt than in calcareous sand.

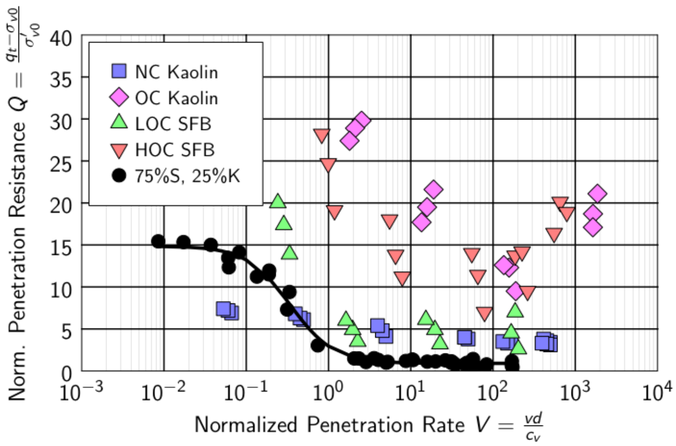

Figure 2. Effect of normalized penetration rate on normalized penetration resistance in five soils. (75% sand, 25% kaolin mixture; lightly and heavily overconsolidated silica flour-bentonite (SFB), and normally consolidated and overconsolidated kaolin data from Schneider et al. 2007).

3.5 *Effect of Penetration Rate on Generated Pore Pressure*

The relationship between the pore pressure parameter (B_q) and normalized velocity (V) in the sand-kaolin mixture is not as clear as the relationship between Q and V (Fig. 3). At normalized velocity V ≈ 0.01, the pore pressure parameter B_q has stabilized at zero and the normalized penetration resistance Q has also stabilized, indicating that behavior is drained for V < 0.01. In the region of V > 20, the relationship between B_q and V is less clear. Previously published results from Schneider et al. (2007) suggested that the pore pressure parameter B_q correlated well with normalized velocity for normally and overconsolidated kaolin samples, but the correlation was poor for silica flour-bentonite mixtures. A possible explanation for the poor correlation in the undrained region is that undrained conditions were induced at both shallow and deep sections of the experiment, which give widely different B_q and significant scatter in the relationship of B_q and V.

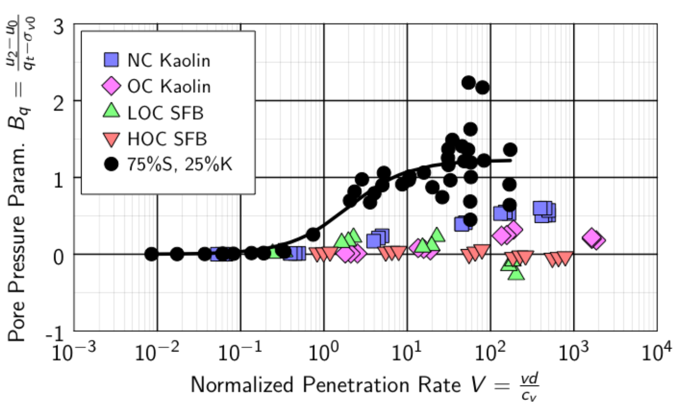

Figure 3. Effect of normalized penetration rate on the pore pressure parameter B_q in five soils. (75% sand, 25% kaolin mixture; lightly and heavily overconsolidated silica flour-bentonite (SFB), and normally consolidated and overconsolidated kaolin data from Schneider et al. 2007).

Schneider et al. (2007) suggested the use of the dimensionless quantity

$$U = \frac{u_2 - u_0}{\sigma'_{vo}} = \left(\frac{u_2 - u_0}{q_t - \sigma_{vo}}\right)\left(\frac{q_t - \sigma_{vo}}{\sigma'_{vo}}\right) = B_q Q \quad (3)$$

where u_2 is the measured pore pressure on the cone shoulder; u_0 is the hydrostatic pore pressure; and σ'_{v0} is the initial vertical effective stress. The sand-kaolin mixture reached a maximum U of approximately 1.2 at V ≈ 15 – 30. Interestingly, the sand-kaolin mixture showed a negative slope beyond normalized velocities of 30, which was not apparent in the B_q – V plot (Fig. 4). The same trend was seen in the silica flour-bentonite mixtures from Schneider et al. (2007), while both the normally and overconsolidated kaolin mixtures maintained positive slopes up to normalized velocities around 1000. Unfortunately, the largest normalized velocity possible within the sand-kaolin mixture was limited to less than 160 due the large vertical coefficient of consolidation of the soil. Therefore it is uncertain if dilation induced negative pore pressures might have been induced at higher normalized velocities within the sand-kaolin mixture; its negative slope suggests that larger shear induced pore pressures may be possible in this intermediate soil just as it was in the silica flour-bentonite.

3.6 *Effect of Penetration Rate on Soil Classification Charts*

Current soil classification techniques (e.g. Robertson 1990) have been developed for cone penetration testing at the ASTM standard penetration rate of 2.0 cm/sec. These classifications are based on the normalized penetration resistance Q, normalized friction ratio F_r, and pore pressure parameter B_q. However, these normalized parameters have all been shown to be dependent on penetration rate. Thus, the utility of classification charts at penetration rates other than 2.0 cm/sec was evaluated.

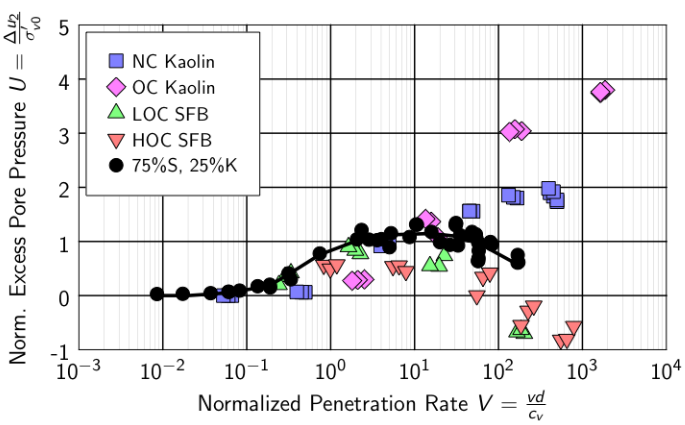

Figure 4. Effect of normalized penetration rate on pore pressure normalized by the initial vertical effective stress in five soils. (75% sand, 25% kaolin mixture; lightly and heavily overconsolidated silica flour-bentonite (SFB), and normally consolidated and overconsolidated kaolin data from Schneider et al. 2007).

The sand-kaolin mixture data points plot along a curve beginning at the B_q = 0 axis (e.g. drained penetration), which decreases in Q and increases in B_q as V increases (Fig. 5). Data from this test move across several classification chart boundaries, which is not surprising since the normalized penetration resistance and pore pressure parameters can vary greatly with normalized velocity. NC kaolin and OC kaolin data from Schneider et al. (2007) also plot along similar curves beginning at or near the B_q = 0 axis, which decrease in Q as B_q increases. Interestingly, the OC kaolin data within the viscous range plotted along the same curve as the drained to undrained transitional points. The silica flour-bentonite mixtures do not show the same trends and plot on both sides of the $B_q = 0$ axis. Therefore, the shapes of the curves in $B_q - Q$ charts can be very different for different soil types.

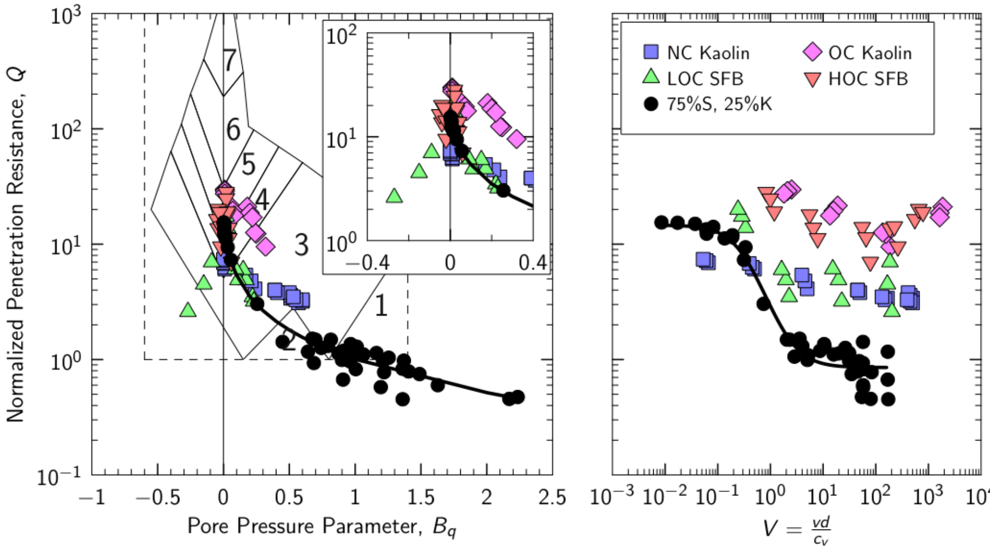

Figure 5. Effect of normalized penetration rate on the use of soil classification charts in five soils with corresponding normalized velocity and normalized penetration resistance plot (75% sand, 25% kaolin mixture; lightly and heavily overconsolidated silica flour-bentonite (SFB), and normally consolidated and overconsolidated kaolin data from Schneider et al. 2007).

4 CONCLUSIONS

Drainage conditions have been shown to be controllable by varying the rate of penetration. Drained conditions in the sand-kaolin mixture appear to occur at normalized velocity $V < 0.01$ while undrained conditions exist for $V > 20$. These limits are in close agreement with those proposed by Finnie & Randolph (1994). Discrepancies in the normalized velocities where drained and undrained conditions begin can be attributed to differences in the selection of the coefficient of consolidation, which controls the location and stretching of the normalized curves. In this paper, an empirical relationship between vertical consolidation stress and the vertical coefficient of consolidation determined from one-dimensional consolidation tests is used, while others have used analytical expressions derived from critical state soil mechanics (e.g. Schneider et al. 2007, Lehane et al. 2009).

Several normalized parameters have been evaluated for the variable penetrate rate test data presented and the normalized penetration resistance (Q) and normalized excess pore pressure (U) provide the best fit to the data from five data sets. The normalized pore pressures parameter (B_q) is shown to have significant scatter for the sand-kaolin mixture when correlated with normalized velocity, which is contradictory to the results presented in Randolph (2004) and Schneider et al. (2007).

Current cone penetration testing characterization methods (e.g. soil classification charts by Robertson et al. 1990) are also shown to be sensitive to penetration rate. The soil classification of each of the five datasets here was shown to change between several soil behavior types and even plotted outside of the original boundaries of the charts. Therefore, the soil classification charts from Robertson et al. (1990) and possibly others are not appropriate for penetration rates other than the penetration rates they are created for. Further research into classification charts for in situ testing must be evaluated if they are to be used for penetration rates other than 2.0 cm/sec.

5 ACKNOWLEDGEMENTS

Support from PEER, the National Science Foundation (OISE#0530151), and the United States Society on Dams (USSD) is gratefully acknowledged. Support from Don Herley, Damian Schmalz, Shane De Catania, Phil Hortin, Binaya Bhattarai, Kristin Hunt, and Claire Bearman is appreciated.

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