Penetration Rate Effects on Cone Resistance: Insights From Calibration Chamber and Field Testing

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Abstract. Cone penetration in mixed or intermediate soils (soils containing mixtures of sand, silt and clay) is neither fully drained nor fully undrained at the standard cone penetration rate of 20 mm/s. Considerable research, mainly relying on centrifuge tests, has been undertaken to quantify the effects of penetration rate (and thus partial drainage) on cone resistance. In this paper, the effects of penetration rate on cone resistance in saturated clayey soils were investigated by performing field tests and miniature cone penetration tests in a calibration chamber. The field tests were performed at sites especially selected to span the range of drainage conditions from fully drained to fully undrained. The calibration chamber tests, using both conical and flat-tip penetrometers, were performed at different penetration rates in two specimens prepared by mixing kaolin clay and sand with different mixing ratios and one-dimensionally consolidateding the mixtures. A correlation between cone resistance and drainage conditions is established based on the cone penetration test results. The transitions from no drainage to partial drainage and from partial drainage to full drainage are defined as a function of penetration rate normalized with respect to the penetrometer diameter and the coefficient of consolidation.

Keywords: cone penetration, CPT, penetration rate, mixed soils.

1. Introduction

The cone penetration test (CPT) has become one of the preferred methods of site characterization partly due to its simplicity, partly as a result of the development of cone resistance-based correlations for footing design (Schmertmann, 1970; Mayne & Poulos, 1999; Lee & Salgado, 2002; Lee *et al.*, 2005; Foye *et al.*, 2006; Lee *et al.*, 2008; O'Loughlin & Lehane, 2010), pile design (Lee & Salgado, 1999; Lee *et al.*, 2003; Jardine *et al.*, 2005; Kolk *et al.*, 2005; Xu *et al.*, 2008; Seo *et al.*, 2009; Foye *et al.*, 2009; Niazi & Mayne, 2013) and liquefaction resistance estimation (Seed & De Alba, 1986; Stark & Olson, 1995; Salgado *et al.*, 1997; Robertson & Wride, 1998; Carraro *et al.*, 2003). The apparent simplicity of the CPT, however, hides considerably complex mechanics (Salgado, 2013). One source of complexity is possible partial drainage during cone penetration.

The standard rate of penetration in a CPT is 20 ± 5 mm/s according to ISO 22476-1 and ASTM D 5778. This standard penetration rate is specified regardless of soil type. Cone penetration at the standard rate is fully drained for clean sand and fully undrained for pure clay. For soils consisting of mixtures of silt, sand and clay, cone penetration may take place under partially drained conditions at the standard penetration rate, depending on the ratios of these three broad particle size groups. This means that use of correlations developed for sand (in which tests would be drained at standard rates of penetration) or clay (in which tests would be undrained at standard rates of penetration) will not work for soil in which penetration at the standard rate takes place under partially drained conditions.

Physically, drainage conditions during penetration are important because, if the penetration rate is sufficiently low for a given clayey soil, the soil ahead and around the advancing cone partially consolidates during penetration, thereby developing greater shear strength and stiffness than it would have under undrained conditions. The closer the conditions are to fully drained during penetration, the higher the value of q_c. Another physical process that is at play for soils with large clay content for penetration under fully undrained conditions is the effect of the rate of loading on shear strength due to the "viscosity" (rate dependence of the shear strength) of clayey soils. The higher the penetration rate is, the larger the undrained shear strength s_u (and therefore q_c) is. These two physical processes - drainage and loading rate effects - have opposite effects on q_c.

A number of studies (Bemben & Myers, 1974; Campanella *et al.*, 1983; Kamp, 1982; Powell & Quarterman, 1988; Rocha Filho & Alencar, 1985; Roy *et al.*, 1982; Tani & Craig, 1995) have considered rate effects in CPT testing for both clays and sands. Results of some field cone penetration tests and centrifuge test results indicated that cone resistance increases and excess pore pressure drops as the penetration rate decreases (Campanella *et al.*, 1983; House *et al.*, 2001; Randolph & Hope, 2004; Rocha Filho & Alencar, 1985; Mahmoodzadeh & Randolph, 2014).

The degree of consolidation during penetration depends on the cone penetration rate, cone diameter, and consolidation coefficient of the soil (Finnie & Randolph, 1994;

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House *et al.*, 2001; Randolph & Hope, 2004; Mahmoodzadeh & Randolph, 2014). These factors can be used to obtain a normalized penetration rate V:

$$V = \frac{vd_c}{c_v}$$

where v = cone penetration rate; d_c = cone diameter; and c_v = coefficient of consolidation that would be obtained from a one-dimensional consolidation test performed on a sample with the same fabric orientation as it would have in the field. As pore pressure is generated during cone penetration, the generated hydraulic gradients in the soil around the cone will determine flow direction. Therefore, normalization with respect with c_v is not necessarily correct. Most results reported in the literature were normalized with respect to c_v, so this normalization will also be used in the present paper. Conceptually, penetration resistance would vary with rate of penetration, as illustrated in Fig. 1, which shows that penetration resistance is highest at low penetration rates, when penetration is drained, and then transitions to its lowest value at sufficiently high rates of penetration. The research questions in connection with this are:

1) Is there a single backbone curve if cone resistance is normalized in some manner, for all soil types?
2) For increasing penetration rates, what are the values of normalized penetration rates V_d and V_u at which penetration transitions to partially drained and then to fully undrained penetration?
3) If V_u is seen, alternatively, as the rate at which penetration resistance stabilizes at its lowest value, how does soil viscosity affect its value?

The centrifuge has been the primary tool used to study these questions. Figure 2 shows results from a few previous studies (Oliveira *et al.*, 2011; Randolph & Hope, 2004; Schneider *et al.*, 2007; Mahmoodzadeh & Randolph, 2014). The soil tested by Randolph & Hope (2004), Schneider *et al.* (2007) and Mahmoodzadeh & Randolph (2014) was a kaolin clay, while the soil tested by Oliveira *et al.* (2011) was silty mine tailings. The plot shows the ratio of normalized cone resistance ($q_{c,p}$ under drained, partially drained or undrained conditions divided by the undrained value of cone resistance $q_{c,u}$) *vs.* the normalized rate $V = vd_c/c_v$ of penetration, discussed earlier. The values of this ratio range between roughly 2.7 and 3.7. The limiting normalized penetration rate for drained penetration varies in a range of roughly 0.01 to 1, but the limiting normalized penetration rate for transitioning from partially to fully undrained penetration varies within a much wider range, from as little as 1 to over 100.

In this paper, the effect of rate on cone resistance is assessed through a series of CPTs performed using a miniature cone in a large calibration chamber and field tests especially designed to investigate rate effects. These experiments complement the body of work developed through centrifuge testing and shed some additional light on the three research questions posed earlier.

2. Field Testing

Kim *et al.* (2008) investigated the effects of penetration rate on cone resistance at two field test sites in the state of Indiana. The advantage of studying rate effects in the field is that the shortcomings of laboratory testing are avoided. The coefficient of consolidation c_v was obtained from consolidation tests performed for two loading stages close to the vertical effective stresses of the corresponding CPT test layers considered in the field. The values of the normalized cone resistance q_t / σ'_v obtained for the two test sites considered are plotted as a function of log V in Fig. 3. With the normalization, the values of q_t / σ'_v drop with increasing V until $V \approx 4$ and then increase only slightly as V increases further. The effect of the cone penetration rate on the excess pore pressure measured is shown in the same figure as a function of log V. The excess pore pressure is nor-

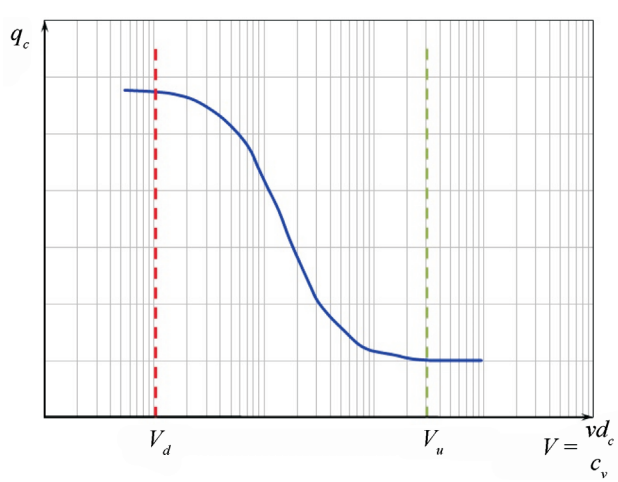

Figure 1 - Conceptual backbone curve for cone penetration resistance *vs.* rate of penetration.

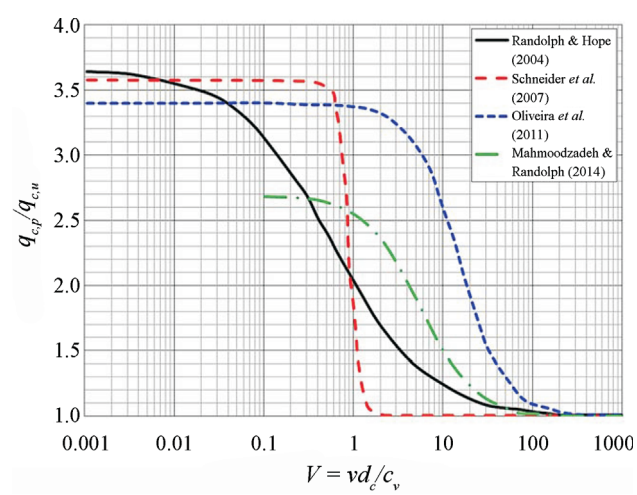

Figure 2 - Backbone curve for CPTs performed in centrifuges (modified after Oliveira *et al.*, 2011).

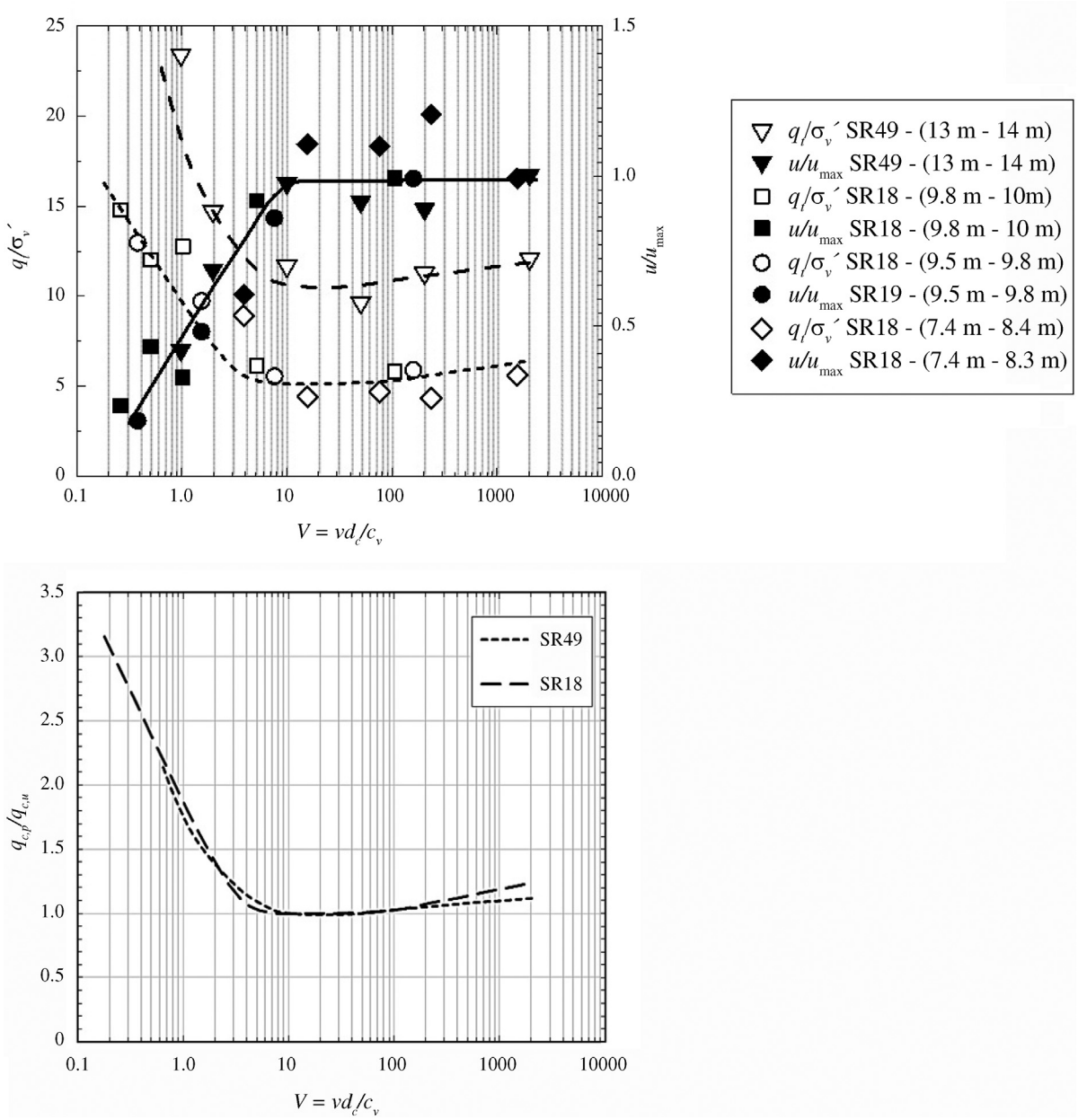

Figure 3 - Field results showing (a) cone penetration resistance *vs.* normalized rate of penetration and (b) backbone curve for CPTs performed in the field.

malized with respect to the maximum value of excess pore pressure measured in a given soil layer. The transition from undrained to partially drained penetration occurs at about $V = 10$.

Since the undrained shear strength s_u (and thus cone resistance measured under undrained conditions) depends on the rate of loading, the value of penetration rate at which penetration transitions from undrained to partially drained penetration (which should be based on pore pressure observations) does not coincide with the point at which the plot of cone resistance *vs.* penetration rate transitions from a range where it is flat to one in which it increases. According to Fig. 3(a) and (b), this transition occurs for $V \approx 10$. In the range between the minimum q_t in Fig. 3 (observed at $V \approx 4$) and $V \approx 10$, q_t would tend to drop because it approaches undrained conditions but would tend to increase because loading rate effects on the soil shear strength start becoming significant. From a practical standpoint, if the goal is to determine the value of V at which penetration resistance stops dropping, then the $V \approx 4$ read from the q_t plot may be of greater interest, but penetration may not be fully undrained at that value of V.

3. Calibration Chamber Cone Penetration Tests

3.1. Overview

Calibration chamber tests are useful in the development of empirical correlations between soil properties and *in situ* test methods such as the CPT. Homogeneous samples can be prepared in the calibration chamber, and the stress state of the soil sample in the chamber can be controlled.

Calibration chamber penetration tests with a miniature cone were performed at the Korea University Calibration Chamber Laboratory in Seoul, Korea (see Fig. 4). The chamber has an inside diameter of 1.2 m and a height of 1.0 m. The top plate of the chamber has 9 holes to provide access for the cone penetrometer. The chamber has a double-wall system, which permits the simulation of K_0 consolidation.

3.2. Normalization of penetration rate and discussion of chamber specimens

In order to evaluate CPT rate effects in clayey soils, cone penetration rates in the calibration chamber tests must cover the whole range of expected drainage conditions (from undrained to fully drained conditions). The normalized penetration rate V is useful to accommodate results obtained from different test conditions, penetrometer sizes, and samples. Results of CPTs performed in the field discussed earlier indicated that the values of V that correspond to the transition from fully undrained to partially drained conditions were between 4 and 10 (Kim *et al.*, 2008). Regarding the other end of the range, centrifuge test results discussed earlier showed that the value of V corresponding to the transition from partially to fully drained conditions could be as low as 0.01.

The range of the penetration rate possible in the chamber tests, based on equipment limitations, was between 20 mm/s and 0.01 mm/s. In planning the experiments, the target range for normalized penetration rate V was $0.01 < V < 30$ in order to fully cover the entire range of drainage conditions. Since the miniature cone diameter is 11.3 mm and the range of cone velocities is constrained by equipment limitations, the variable left to control was c_v.

3.3. Coefficient of consolidation and mixing ratios

A total of 16 flexible-wall permeameter tests were performed in general accordance with ASTM D 5084: ten tests with mixtures of Ottawa sand (ASTM C778 Graded) and kaolin clay (10%, 14.5%, 15%, 16.6%, 19%, 21%, 21.8% 24%, and 29.1% of kaolin clay), and six tests with mixtures of Jumunjin sand and kaolin clay (16%, 17.5%, 18.5%, 22%, 22.2%, and 25% of kaolin clay). Figure 5 shows the grain size distribution curves of Ottawa sand, Jumunjin sand and kaolin clay.

Figure 6 shows the percentage of clay of the soil mixtures studied *vs.* c_v in log scale for an isotropic confining stress of 150 kPa. From this graph, it can be seen that the log c_v has an approximately linear relationship with the clay content of the soil mixtures. Based on the c_v values shown in Fig. 6, values of V were calculated for v = 20 mm/s and D = 11.3 mm (the miniature cone diameter). For the target value of 60 for V (twice as high as the upper limit of 30 suggested in the literature) required to allow fully undrained conditions at a penetration rate of 20 mm/s, a soil with $c_v \leq 3.8 \times 10^{-6}$ m^2/s was found to be needed. Based on the flexible-wall test results, a mixing ratio of 25% kaolin clay and 75% Jumunjin sand ($c_v = 3.45 \times 10^{-6}$ m^2/s) was selected for the first calibration chamber sample. This sample al-

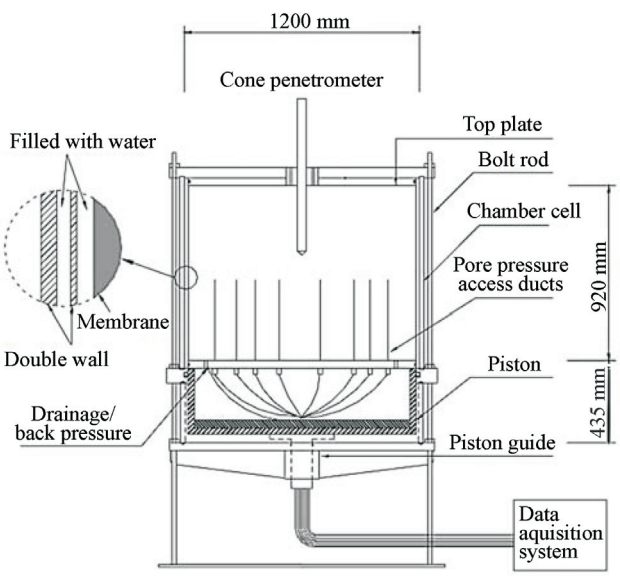

Figure 4 - Schematic view of the flexible wall calibration chamber (Kim *et al.*, 2006).

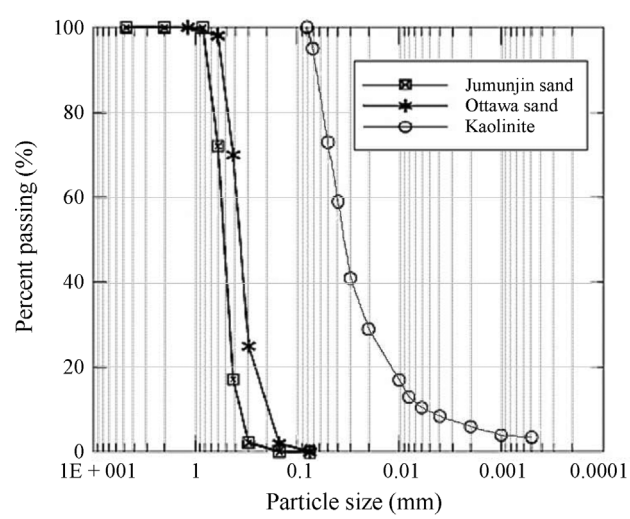

Figure 5 - Grain size distribution of Jumunjin sand, Ottawa sand, and kaolin clay (modified after Kim *et al.*, 2006).

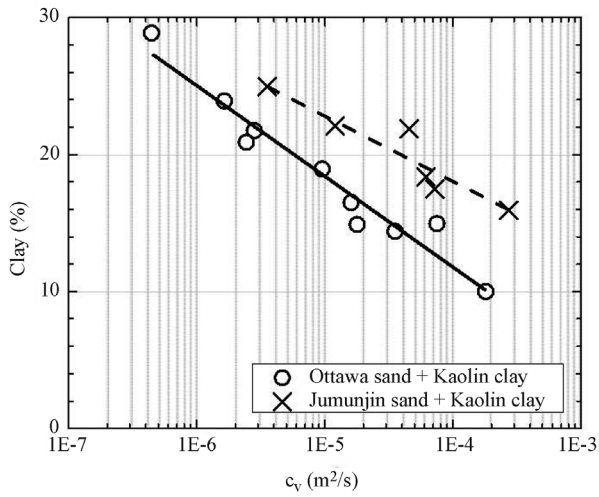

Figure 6 - Percentage of clay of soil mixtures *vs.* c_v.

lowed tests at $V = 0.033$ to $V = 66$ for $D = 11.3$ mm and v between 0.01 mm/s and 20 mm/s.

As previously discussed, a V as low as 0.01 was believed to be required to allow penetration under fully drained conditions. In order to achieve that value of V, the other chamber specimen was prepared with a mixing ratio of 18% clay and 82% Jumunjin sand ($c_v = 6.9 \times 10^{-5}$ m^2/s). The value of V for this soil mixture was equal to 0.0016 for $v = 0.01$ mm/s and $D = 11.3$ mm.

3.4. Cone penetration test program

The miniature piezocone penetrometer used in the calibration chamber tests has a diameter of 11.3 mm (projected cone area = 100 mm^2), a cone apex angle of 60° and a net area ratio of 0.62. The miniature cone, which was borrowed from Fugro B.V., Netherlands, is equipped with a friction sleeve and a porous stone to measure pore pressure just behind the tip. All pore pressure measurements should be considered to be related to where the porous stone is located, so comparison of results across experiments should be done carefully. A flat tip was manufactured specially for the minicone and used to investigate the effect of the tip shape on penetration test results.

Minicone penetration tests were performed at nine different penetration rates, ranging from 20 mm/s to 0.01 mm/s, in the specimen made with 25% kaolin clay and 75% Jumunjin sand by weight (referred to as P1), which had a floating fabric (Carraro *et al.*, 2009, Carraro *et al.*, 2003; Salgado *et al.*, 2000). Eight different penetration rates, ranging from 20 mm/s to 0.05 mm/s, were used in the tests in the specimen made with 18% kaolin clay and 82% Jumunjin sand (referred to as P2), which has a non-floating fabric. The CPTs were performed down to a depth of around 750 mm (out of the 950 mm specimen height). This penetration depth was sufficient to obtain stable cone resistance values for more than two different penetration stages. Therefore, the penetration test in each hole was done in two stages with two different penetration rates.

4. Results of Miniature Cone Penetration Tests

4.1. Penetration tests in specimen P1

Results of tests performed with both the conical and flat tips in specimen P1 are presented in Fig. 7. The cone resistance q_t is the corrected cone resistance for the pore pressure acting on the shoulder area behind the cone tip. Figure 7(a) shows that q_t for v of 20 mm/s and 8 mm/s is almost the same, around 0.7 MPa, and the corresponding excess pore pressures are 295 kPa and 270 kPa, respectively. These results show that, for v of 20 mm/s and 8 mm/s, cone penetration occurred under undrained conditions. The values of q_t started to increase slowly as v decreased from 8 mm/s to 0.25 mm/s. The measured average q_t values showed an increase of 30% (from 0.7 MPa to 0.91 MPa) for a reduction in v from 8 mm/s to 0.25 mm/s, whereas the pore pressure decreased about 20% for the same change in v. The values of q_t increased from 0.91 MPa to 3.14 MPa (or about 3.5 times) for a change in v from 0.25 mm/s to 0.02 mm/s. For the same change in v, the excess pore pressure dropped from 222 kPa to 8 kPa. The decrease in excess pore pressure to practically zero indicates that the drainage conditions changed from partially drained to drained. The values of q_t and excess pore pressure for $v = 0.01$ mm/s (for which conditions are also drained) are almost the same as the values measured for $v = 0.02$ mm/s.

The miniature penetration tests with a flat tip were performed to investigate the impact of the shape of the tip on penetration resistance. The results obtained using both a cone tip and a flat tip under the same conditions provide insights into the relationship between cone resistance and limit unit pile base resistance. The average values of flat-tip resistance and pore pressures are also presented in Fig. 7.

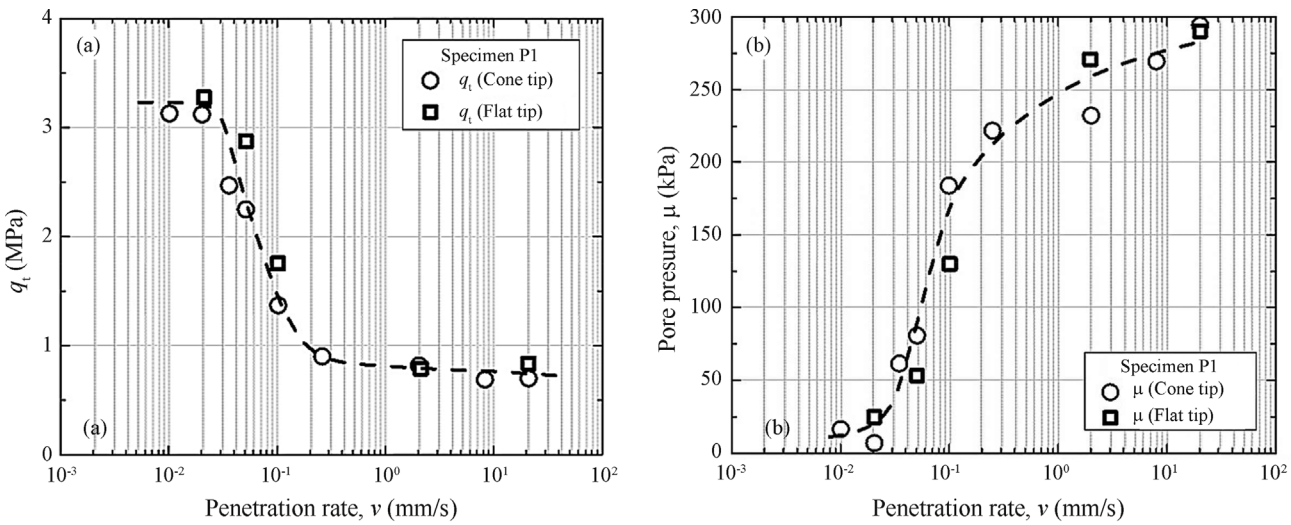

Figure 7 - Effect of penetration rate on (a) q_t and (b) pore pressure u for specimen P1.

The overall flat tip resistances obtained in P1 for the entire penetration rate range are similar to the corresponding cone resistances. The transition points indicating change in drainage conditions seem to be identical for the two tip shapes.

4.2. Penetration tests in specimen P2

The penetration tests performed in P2 focused on identifying the transition between partially drained and fully drained conditions. The steady-state values of q_t and excess pore pressure *vs.* penetration rate for specimen P2 are shown in Fig. 8(a) and Fig. 8(b). While the penetration rate decreased from 20 mm/s to 2 mm/s, the values of q_t increased from 1.28 MPa to 1.65 MPa, and the excess pore pressure decreased by about 40%. This drop in excess pore pressure indicates that the penetration was likely not fully undrained even with the 20 mm/s maximum v, and it certainly was not so for 2 mm/s. The transition from partially drained to fully drained conditions took place for a penetration rate of about 0.1 mm/s. The average q_t at fully drained conditions was approximately 4 MPa.

The shape of the tip influenced the values measured in the penetration tests performed in P2. For v = 20 mm/s, the resistance of the flat tip was 2.1 MPa, 64% higher than the cone resistance measured at the same speed. Over the whole range of penetration rates, the flat tip resistance values were higher than the corresponding cone resistance values, but this difference reduced as drainage increased. Under fully drained conditions, for v = 0.1 mm/s, the flat tip resistance was 4.4 MPa, and the cone resistance was 4.0 MPa, a more modest difference, practically justifying an assumption often made for sands that $q_c \approx q_{bL}$, where q_{bL} is the limit unit base resistance of a pile in sand under the

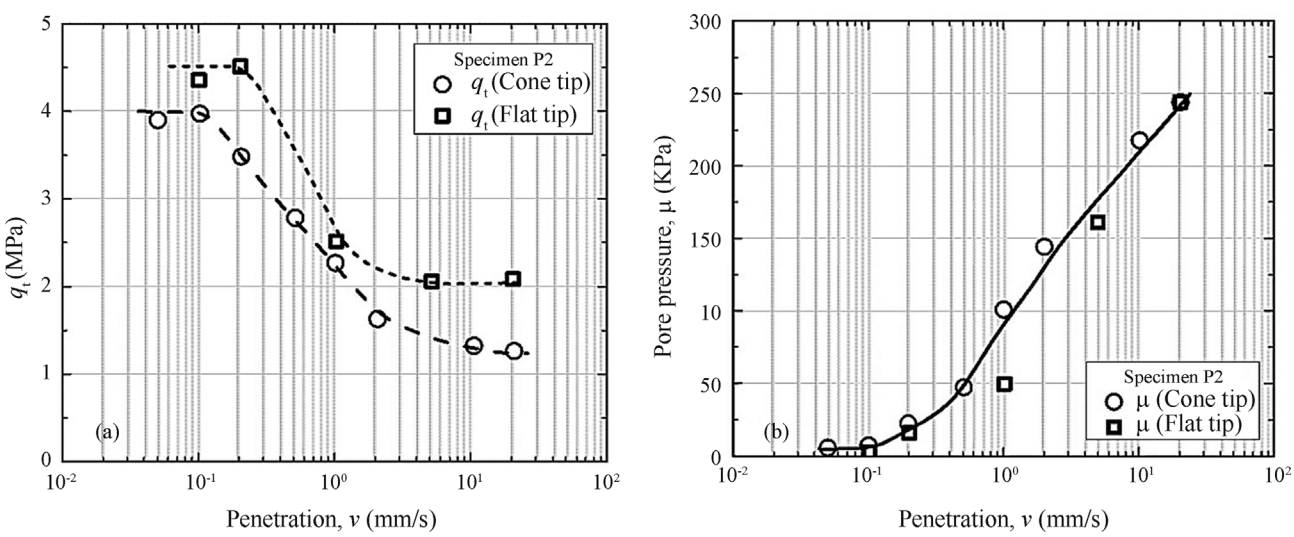

Figure 8 - Effect of penetration rate on (a) q_t and (b) pore pressure u for specimen P2.

same conditions as those under which q_c was measured, so long as the ratio of pile to particle size is sufficiently large (a ratio as low as 20 might be sufficient). Only a small difference in the excess pore pressure measurements was observed.

4.3. Normalized cone resistance *vs.* normalized penetration rates

The results of the penetration tests in the two different specimens can be plotted in terms of the cone resistance normalized by vertical effective stress and the normalized penetration rate V. The values of c_v used for normalization were calculated using the data obtained from the calibration chamber specimen consolidation, which was conducted under perfect 1D conditions, without sidewall resistance. The measured values of c_v are equal to 3.5 x 10^{-6} m^2/s for P1 and 3.1 x 10^{-5} m^2/s for P2.

The normalized results for P1 and P2 are shown in Fig. 9 as a function of log V. The plots in Fig. 9 (a) suggest that the cone resistance increases when V drops below approximately 1, with the transition between partially drained and fully drained conditions occurring around $V \approx 0.05$. According to the normalized excess pore pressure shown in Fig. 9 (a), the transition from undrained to partially drained penetration occurs around $V \approx 10$, and the transition from partially drained to fully drained conditions occurs around $V \approx 0.05$. The reason for the discrepancy between the penetration rate at which q_t stabilizes and that at which the excess pore pressure stabilizes can be explained by the superposition of the two main rate effects. In the penetration range between $V \approx 1$ and $V \approx 10$, q_t would tend to drop because it approaches partially drained conditions but would tend to increase because loading rate effects due to viscosity effects start taking place. From a practical standpoint, if the goal is to determine the value of V at which penetration resistance is stable, then the $V \approx 1$ read from the q_t plot may be of greater interest. The backbone curves in Fig. 9 (b) show the effect of fabric on the normalized cone resistance values. The maximum ratio of $q_{c,p}/q_{c,u}$ for specimen P1, which has a floating fabric, is about 4.7, while that for specimen P2, which has a non-floating fabric, is about 2.5. This is likely related to the different distribution of excess pore pressure developing ahead of the advancing cone, with the specimen with floating fabric experiencing greater excess pore generation [see Fig. 7(b) and Fig. 8(b)], and thus offering relatively less resistance to the penetration of the cone under partially drained conditions. These results highlight the difficulty in assessing partial drainage effects for *in situ* soils consisting of mixtures of sand, silt and clay, where fabric effects can affect the measured cone resistances.

The results presented in this paper may be used to obtain the limiting values of c_v that clayey soils would have to have for penetration to take place under drained and undrained conditions for given values of penetration rate and

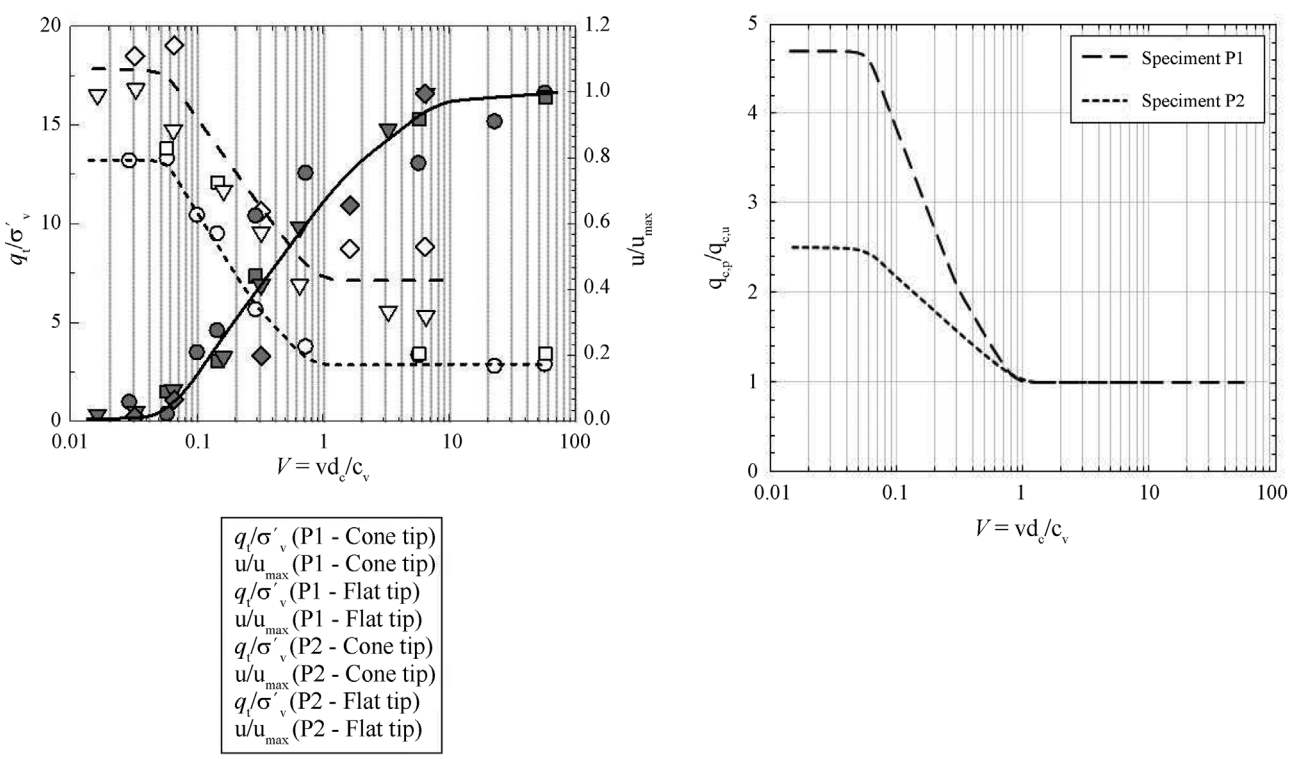

Figure 9 - Results for specimens P1 and P2: (a) cone resistance normalized with respect to vertical effective stress and excess pore pressure normalized with respect to its maximum observed value *vs.* normalized penetration rate V and (b) backbone curves (in terms of ratio of q_c at any rate of penetration to q_c under undrained conditions) for specimen P1 and P2.

cone diameter. As discussed previously, the drainage conditions change from undrained to partially drained at a value of $V \approx 10$, which corresponds to a $c_v \approx 7.1 \times 10^{-5}$ m^2/s for the standard cone penetration rate (20 mm/s) and diameter (35.7 mm). However, because of the offsetting effect of rate-dependent shear strength, cone resistance starts to plateau for $V > 1$, which corresponds to a $c_v \approx 7.1 \times 10^{-4}$ m^2/s. Therefore, we can conclude that undrained cone resistance is expected to be measured in CPTs performed with the standard cone at the standard rate in soils having c_v values less than roughly 10^{-3} to 10^{-4} m^2/s. At the other end of the spectrum, the test results suggest that a value of c_v larger than about 1.4×10^{-2} m^2/s (or roughly 10^{-2} m^2/s) is necessary for fully drained conditions to be achieved with a standard CPT.

5. Discussion

Table 1 summarizes what has been learned so far in connection with the dependence of cone resistance on rate of penetration for soils tested so far (kaolinite, clay, sandy clay, silty mine tailings) in the centrifuge, calibration chamber and field. V_d is the rate below which penetration is drained. V_u is the rate above which the cone resistance stabilizes at its lowest value. The value approximates, but not necessarily coincides with, the rate above which penetration is undrained, as discussed previously. It is apparent from the table that there are differences in the values observed for the limiting rates between centrifuge on the one hand and chamber and field tests on the other. The centrifuge test results also appear to suggest that these rates could vary within relative wide ranges.

The relatively wide ranges observed in centrifuge results may be due to fundamental differences in soil behavior as well as details of the penetration boundary-value problem. The centrifuge tests that led to the backbone curves in Fig. 2 were performed in a kaolinite sample and a silty soil. A clear difference between clay and silt, both of which have been used in research on this topic, is that clay develops planes of failure with aligned particles and has a residual shear strength less than critical, but silt does not. Differences in fabric between test models also would have an effect on the gradients of strength and drainage around the advancing cone. Spatial variation of rates of loading and degree of consolidation around the advancing cone also place limits on achievement of a single backbone curve, as well as on normalization of rates of penetration with respect to c_v. The backbone curves are likely to depend not only on the nature of the soil but also its state (void ratio, effective stress state, over-consolidation ratio and fabric), and generalizations may not be achievable before significant amount of testing is done for soils spanning the whole range of particle sizes and soil state.

Table 1 - Approximate values of the rates at which penetration transitions from drained to partially drained and partially drained to drained penetration and ratio of drained to undrained penetration resistance for the field, chamber and centrifuge testing.

Key quantities	Field	Chamber	Centrifuge
V_d	< 1	0.05	0.01-1
V_u	10	1	2-100
$q_{c,\ drained}/q_{c,\ undrained}$	undefined	2.5-4.7	2.7-3.7

The lesson to CPT performance and interpretation in practice from research done on this topic so far is clear and relatively straightforward: the use of the standard 20 mm/s should no longer be the norm. Every effort should be made to perform CPTs under either fully drained or fully undrained penetration whenever feasible. The alternative is to interpret tests performed under partially drained penetration, which is still very challenging. In order to avoid penetration under partial drainage and the more challenging interpretation of such tests, CPTs in sand-controlled soils should be performed as slowly as possible to guarantee full drainage, while CPTs in clay-controlled soils should be performed as fast as required to ensure fully undrained penetration.

6. Summary and Conclusions

The main focus of the research presented in this paper was to evaluate and quantify the factors affecting the results of cone penetration testing performed at penetration rates leading to drainage conditions ranging from fully drained to fully undrained. Rate effects and the effects of drainage conditions around the cone tip during penetration were studied. Results from a series of penetration tests performed in the centrifuge, the calibration chamber and the field conducted at various penetration rates were presented, and the transition from undrained to partially drained and then to fully drained penetration was investigated in terms of a normalized penetration rate.

The ratio of cone resistance measured under drained to that under undrained conditions observed in the calibration chamber tests in clay samples was 2.5 to 4.7. The transition from undrained to partially drained conditions occurred for V values approximately equal to 10. For V between approximately 10 and 1, cone resistance was fairly stable because of the offsetting effects on shear strength of loading rate and drainage rate. The transition from partially drained to fully drained conditions occurred at $V \approx 0.05$. From these limiting V values, it is possible to obtain limiting values of c_v required for fully drained and fully undrained penetration for a given cone and penetration rate for the test soil. For soils like the soil tested in the calibration chamber tests reported here having c_v values less than about 7.1×10^{-5} m^2/s ($V = 10$), standard penetration ($v = 20$ mm/s and $D = 35.7$ mm) takes place under undrained conditions, whereas for c_v values greater than about 1.4×10^{-2} m^2/s ($V = 0.05$), standard penetration takes place under drained conditions.

The fact that results from centrifuge tests on clay and silt are not in agreement and that no agreement can be found between the centrifuge test results and the calibration chamber test results on clay and a sandy clay tested in the calibration chamber suggests that a single backbone curve that would apply to all soils likely does not exist. Significant further testing with a variety of soils in a variety of conditions is required to advance understanding of penetration rate and its relationship to drainage rate. In order to avoid the challenges that the limited understanding of this relationship presents to interpretation of CPT results, it may be advantageous to vary the rate of penetration during a test, where possible, to guarantee either full drainage or no drainage during penetration.

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