Penetration rate effects on cone resistance measured in a calibration chamber

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ABSTRACT: In this paper, the effects of penetration rate on cone resistance in saturated clayey soils were investigated by performing miniature cone penetration tests in a calibration chamber. These tests, using both a conical and flat-tip penetrometers, were performed at nine and eight different penetration rates, respectively, in two specimens prepared by mixing kaolin clay and Jumunjin sand with different mixing ratios and consolidated to a K_0 condition. The mixing ratios of these two specimens were decided based on results of flexible-wall permeameter tests performed on clayey sand mixtures prepared at various mixing ratios. A correlation between cone resistance and drainage conditions was established based on the cone penetration test results. The transition from no drainage to partial drainage and from partial drainage to full drainage were defined as a function of penetration rate normalized with respect to the penetrometer diameter and the coefficient of consolidation.

1 INTRODUCTION

The cone penetration test (CPT) has been widely used throughout the world because it is the most effective *in situ* test method for obtaining continuous and reliable soil properties. The standard rate of penetration in a CPT is 20±5mm/s according to the International Reference Test Procedure (IRTP) and the ASTM standard (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. However, the fact that the penetration rate affects the value of cone penetration resistance q_c for these soils was not taken into account at the time standards were prepared for the CPT. 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 consolidates during penetration, thereby developing larger 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" of the clayey soil. The higher the penetration rate is, the larger the undrained shear strength s_u and q_c are. These two physical processes – drainage and loading rate effects – have opposite effects on q_c.

A number of studies (Bemben & Myers 1974, Roy et al. 1982, Campanella et al. 1983, Kamp 1982, Rocha Filho & Alencar 1985, Powell & Quarterman. 1988, 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, Rocha Filho & Alencar 1985, House et al. 2001, Randolph & Hope 2004). In this paper, the change in cone resistance caused by changes in cone penetration rate *v* in clayey soils is investigated. The rate effect is assessed through a series of CPTs using a miniature cone in a large calibration chamber.

2 CALIBRATION CHAMBER CONE PENETRATION TESTS

2.1 *Overview*

Calibration chamber tests are useful for 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 that 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 (KUCCL) in Seoul, Korea. 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 (Kim 2005). A schematic representation of the chamber system is shown in Figure 1.

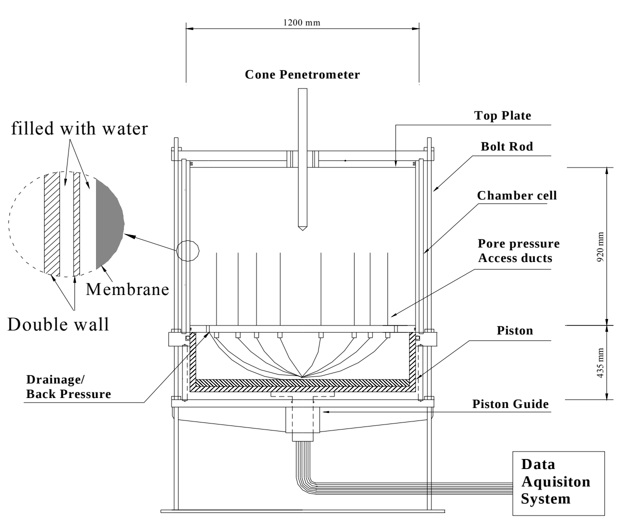


Figure 1. Schematic view of the flexible wall calibration chamber.

2.2 *Normalization of Penetration Rate and Discussion of Chamber Specimens*

The degree of consolidation during penetration depends on the penetration rate, penetrometer diameter, and coefficient of consolidation of the soil (Finnie & Randolph 1994, House et al. 2001, Randolph & Hope 2004). These factors can be used to obtain a normalized, dimensionless penetration rate V:

$$V = \frac{vD}{c_v} \qquad (1)$$

where v = penetration rate; D = cone diameter; c_v = coefficient of consolidation. This normalized penetration rate V has been successfully used for the data analysis of various penetration tests (Finnie & Randolph 1994, House et al. 2001, Randolph & Hope 2004).

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 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). According to Finnie and Randolph (1994), House et al. (2001), and Randolph and Hope (2004), the transition from fully undrained to partially drained conditions obtained from centrifuge tests is in the $10 < V < 30$ range. Regarding the other end of the range, the centrifuge test results by Finnie & Randolph (1994) showed that the value of V corresponding to the transition from partially to fully drained conditions was as low as 0.01.

The allowable range of the penetration rate in the chamber tests based on equipment limitations was between 20 mm/s to 0.01 mm/s. In planning the experiments, we worked under the requirement that this penetration rate range must correspond to $0.01 < V < 30$ in order to fully cover the entire range of drainage conditions. Since the miniature cone diameter is set to 11.3 mm and the range of cone velocities is set by equipment limitations, the variable left to control was c_v.

2.3 *Coefficient of Consolidation estimation and mixing ratio determination*

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). The grain size distributions of Ottawa and Jumunjin sands and kaolin clay are shown in Figure 2.

Figure 3(a) shows the percentage of clay of the soil mixtures studied versus 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. 3(a), values of V were calculated for v = 20 mm/s and D = 11.3 mm (the miniature cone diameter). The variation of V with the clay percentage of the soil mixtures is shown in Figure 3(b). For the target value of 60 for V (twice as high as the upper limit of 30 suggested in the literature) to allow fully undrained conditions at a penetration rate of 20 mm/s, a soil with $c_v \leq 3.77 \times 10^{-6}$ m^2/s was found to be needed. Based on the flexible-wall test results, a mixing ratio of 25 %

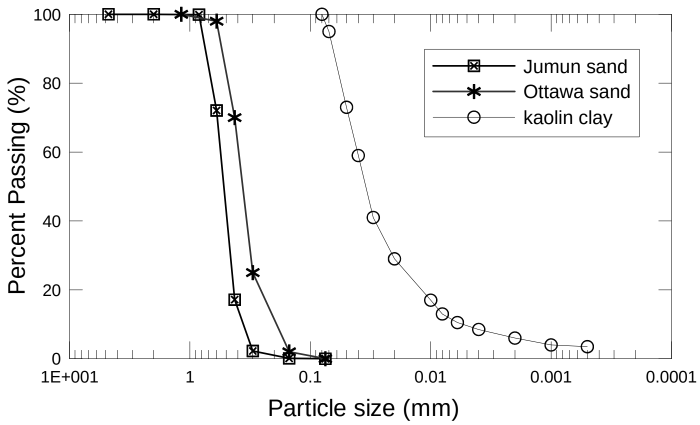


Figure 2. Grain size distribution of Jumunjin sand, Ottawa sand, and kaolin clay.

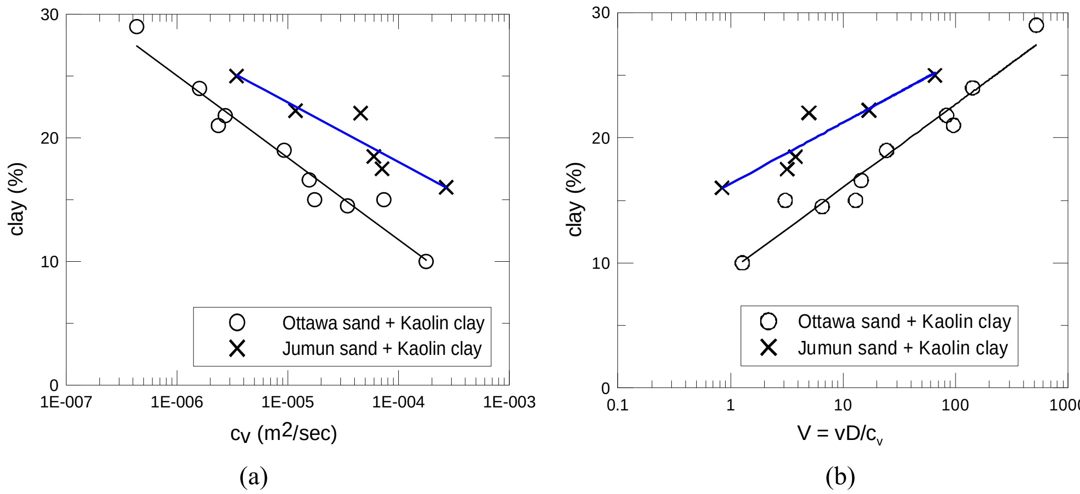


Figure 3. Percentage of clay of soil mixtures versus (a) c_v and (b) V at a confining stress of 150 kPa.

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 allowed 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 = 0.01mm/s and D = 11.3mm.

2.4 *Cone Penetration Test Program*

The miniature piezocone penetrometer used in the calibration chamber tests has a projected cone area of 1cm^2, a diameter of 11.3 mm, and a cone apex angle of 60°. The cone was borrowed from Fugro B.V., Netherlands. It is equipped with a friction sleeve as well as with a porous filter to measure pore pressure just behind the tip. In this research, 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 conducted 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). 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). The CPTs were conducted 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.

3 RESULTS OF MINIATURE CONE PENETRATION TESTS

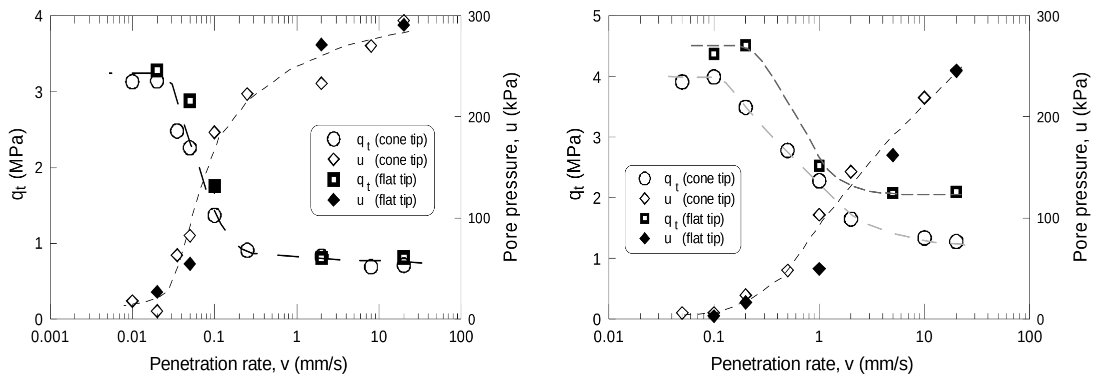
3.1 *Results of Penetration Tests Performed in Specimen P1*

Results of tests performed with both the conical and flat tips in specimen P1 are summarized in Figure 4. The cone resistance q_t is the corrected cone resistance for the pore pressure acting on the shoulder area behind the cone tip. Figure 4(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.

A series of 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 Figure 4. The overall flat tip resistances obtained in P1 for the entire penetration rate range are practically equal to the corresponding cone resistances. The transition points indicating change in drainage conditions seem to be identical for the two tip shapes.

3.2 *Results of Penetration Tests Performed in Specimen P2*

The penetration tests performed in P2 focused mainly on identifying the transition between partially drained and fully drained conditions. The steady-state values of q_t and excess pore pressure versus penetration rate are shown in Figure 4(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



(a) (b)

Figure 4. Effect of penetration rate on q_t and pore pressure for (a) specimen P1 and (b) specimen P2.

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 around 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 much 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 same conditions as those under which q_c was measured. Only a small difference in the excess pore pressure measurements was observed.

3.3 *Normalized Cone Resistance versus 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 3.5×10^{-6} m^2/s for P1 and 3.1×10^{-5} m^2/s for P2.

The normalized results for P1 and P2 are shown in Figure 5, as a function of log V. The plots in Figure 5(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 ≈ 0.05. The plots of normalized excess pore pressure shown in Figure 5(b) show that the transition from undrained to partially drained penetration occurs around V ≈ 10, and the transition from partially drained to fully drained conditions occurs around V ≈ 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 ≈ 1 and V ≈ 10, q_t would tend to drop because it approaches partially drained conditions but would tend to increase because loading

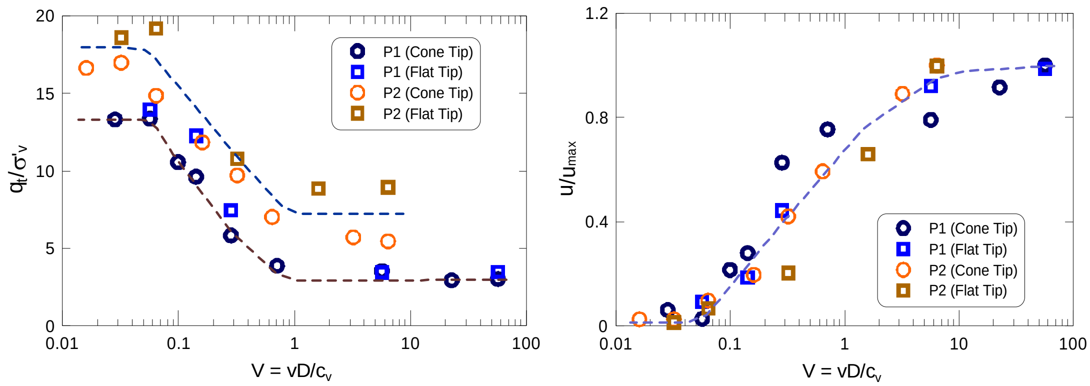


Figure 5. Variation of (a) normalized cone resistance and (b) normalized excess pore pressure, with normalized penetration rate V.

rate effects due to viscosity effects start taking place. There the loading rate effect offsets the changing drainage effect. From a practical standpoint, if the goal is to determine the value of V at which penetration resistance is stable, then the V ≈ 1 read from the q_t plot may be of greater interest.

The results may be used to obtain the limiting values of c_v that soils would have to have for penetration to take place under drained and undrained conditions for given values of penetration rate and cone diameter. As discussed previously, the drainage conditions change from undrained to partially drained at a value of V ≈ 10, which corresponds to a $c_v \approx 7.1\times10^{-5}$ m²/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, the cone resistance starts to plateau for V > 1, which corresponds to a $c_v \approx 7.1\times10^{-4}$ m²/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} m²/s. On the other end of the spectrum, our results suggest that a value of c_v larger than about 1.4×10^{-2} m²/s (or roughly 10^{-2} m²/s) is necessary for fully drained conditions to be achieved with a standard CPT.

4 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 in saturated clayey soils. Rate effects and the effects of drainage conditions around the cone tip during penetration were studied. Results from a series of penetration tests in the calibration chamber 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 was 3 to 4. 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 ≈ 0.05. From these limiting V values, we can obtain the limiting values of c_v required for fully drained and fully undrained penetration for a given cone and penetration rate. For soils having c_v values less than about 7.1×10^{-5} m^2/s (V = 10), standard penetration (*v* = 20 mm/s and D = 35.7mm) 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. Until more research on the topic allows refinement of these limiting values of c_v, the values we propose here may be used to guide the interpretation of cone penetration tests. This is important because, while understanding of CPT interpretation under both drained and undrained conditions is reasonably good, if tests are performed in the partially drained range and an attempt to interpret the results is made with methods for either drained or undrained penetration, the results of that interpretation will be in error.

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REFERENCES

Bemben, S.M., & Myers, H.J. 1974. The influence of rate of penetration on static cone resistance in Connecticut river valley varved clay. *Proc., European Sym. on Penetration Testing*, Stockholm, 2.2: 33-34.

Campanella, R.G., Robertson, P.K., & Gillespie, D. 1983. Cone penetration testing in deltaic soils. *Can. Geotech. J.*, 20(1): 23-35.

Finnie, I.M.S. & Randolph, M.F. 1994. Punch-through and liquefaction induced failure of shallow foundations on calcareous sediments. *Proc., 17th Int. Conf. on the Behavior of Offshore Structures*, Boston, 1: 217-230.

House, A.R., Oliveira, J.R.M.S., & Randolph, M.F. 2001. Evaluating the coefficient of consolidation using penetration tests. *Int. J. of Physical Modeling in Geotechnics*, 1(3): 17-26.

Kamp, W.G.B te 1982. The influence of the rate of penetration on the cone resistance 'q_c' in sand. *Proc., 2nd European Sym. on Penetration Testing*, ESOPT-II, Amsterdam, 2: 627-633.

Kim, T. J. 2005. Dissipation of pore water pressure due to piezocone penetration in OC clay, Ph.D Dissertation, Korea University, Seoul, Korea.

Kim, K., Prezzi, M., Salgado, R., & Lee, W. 2008. Effect of penetration rate on cone penetration resistance in saturated clayey soils. *J. of Geotech. Geoenviron. Eng.*, 134(8): 1142-1153.

Powell, J.J.M & Quarterman, R.S.T. 1988. The interpretation of cone penetration tests in clays, with particular reference to rate effects. *Proc. Int. Sym. On Penetration Testing*, Orlando, 2: 903-909.

Randolph, M.F. & Hope, S. 2004. Effect of cone velocity on cone resistance and excess pore pressures. *Proc. Int. Sym. on Eng. Practice and Performance of Soft Deposits,* Osaka: 147-152.

Rocha Filho, P. & Alencar, J.A. 1985. Piezocone Tests in the Rio de Janeiro soft clay deposit. *Proc. XI Int. Conf. Soil Mech. Found. Eng.*, San Francisco, 2: 859-862.

Roy, M., Tremblay, M., Tavenas, F. & Rochelle, P. L. 1982. Development of pore pressure in quasi-static penetration tests in sensitive clay. *Can. Geotech. J.*, 19(2): 124-138.

Tani, K. & Craig, W.H., 1995. Bearing capacity of circular foundations on soft clay of strength increasing with depth. *Soils and Foundations*, 35(4): 21-35.