Laboratory investigation on the effect of grain size distribution of granular material on cone penetration test results

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ABSTRACT
This paper initially compares and discusses a majority of correlations of (q_c) and (f_s) with typical geotechnical parameters such as relative density (D_r), the effective overburden pressure (σ'_v), void ratio (e), mean grain size (D_{50}), the degree of uniformity (C_u), lateral stress (σ'_h), mean confinement pressure (σ'_m), overconsolidation (OCR), and angularity. The paper then presents the results of a series of experimental simulations for cone penetration test (CPT) on both polydisperse spherical glass beads and natural sands samples with different mechanical properties as well as different loading conditions. Stress-strain records along the soil samples are monitored during the tests. Results obtained for (q_c) and (f_s) are correlated with such geotechnical parameters and the corresponding graphs are plotted in order to predict the real behavior of natural soils in the field.

RÉSUMÉ
Ce papier compare et discute d'abord de la majorité des corrélations de (q_c) et (f_s) avec les paramètres géotechniques typiques tels que la densité relative (D_r), la contrainte effective (σ'_v), l'indice des vides (e), la taille moyenne des particules (D_{50}), le degré d'uniformité (C_u), la contrainte latéral (σ'_h), la contrainte moyenne de confinement (σ'_m), le degré de surconsolidation (OCR), l'âge et l'angularité. L'article présente ensuite les résultats d'une série de simulations expérimentales pour l'essai de pénétration du cône (CPT) sur des billes de verre sphérique polydisperses et sur des échantillons de sables naturels avec des propriétés mécaniques différentes, ainsi que des conditions de chargement différentes. Les contrainte-déformation le long de l'échantillon de sol sont surveillées et enregistrées pendant les essais. Les résultats obtenus pour (q_c) et (f_s) sont corrélés avec les paramètres géotechniques et les graphiques correspondants sont tracés afin de prédire le comportement réel des sols naturels in-situ.

1 INTRODUCTION

Investigating the effect of the soil mechanical parameters on the cone penetration test results (q_c) and (f_s) is a unique challenge for geotechnical engineers. Although the engineering experience shows that wide variations in (q_c) and (f_s) values can occur as between different sands due to the variation of the nature and the mechanical characteristics of the sands such as; relative density (D_r), Void ratio (e), mean particle size (D_{50}), coefficient of uniformity (C_u), overburden pressures (σ'_v), and mean confinement pressure (σ'_m), stress history and aging.

This paper presents data of a series of experimental simulations for cone penetration test (CPT) on both polydisperse spherical glass beads and natural sands samples with different mechanical properties as well as different loading conditions. The purpose of using glass beads is the ability to start a parametric study on D_{50} (e.g. Ghali et al., 2014). In fact, parametric study for the above mentioned factors is a very difficult task as most of these factors not only affect (q_c) and (f_s) values but also affect each other by somehow. Glass beads allow the elimination of the effects of angularity and stress history under certain D_r, σ'_v, and coefficient of earth pressure at rest (K_0). Also using glass beads allow the verification of the results obtained from a DEM software developed by Hydro-Quebec to simulate the CPT. Procedures and driving method were fixed in all carried out tests.

2 BACKGROUND INFORMATION

Since the penetration resistances (q_c) and (f_s) basically depends on the relative density and the stresses (e.g. Salgado et al. (1997), and Tran, C. (2005)), general relations have been presented as follow:

$$q_c = f\left(D_r, \sigma'_v, \sigma'_h\right) \quad [1]$$

$$R_f = \left(\frac{f_s}{q_c}\right)[\%] \quad [2]$$

where:
(q_c) is the cone-tip resistance, (f) is a function of D_r, σ'_v, and σ'_h.
(R_f) is the friction ratio, (f_s) is the sleeve friction.

Also some previous studies have been briefly presented as follows; Schmertmann's (1978) stated some correlations which is more applicable to sands of high compressibility, while the correlation by Baldi et al. (1982, 1985, & 1986) was developed for sands of medium compressibility. Similar correlations have also been proposed by Robertson and Campanella (1983). Kulhawy and Mayne, (1991) collected some field data of CPT and relative density D_r for 24 different sands and established the following general relation to correlate the CPT tip resistance q_c with the relative density:

$$D_r^{\,2} = \left(\frac{1}{Q_F}\right)\left[\frac{q_c / P_a}{(\sigma_v^{'} / P_a)^{0.5}}\right] \qquad [3]$$

where:
P_a represents atmospheric pressure ≈ 100 kPa; Q_F is an empirical constant determined by least-square regression analyses for normally consolidated sands of low, medium and high compressibility to be 332,305, and 278 respectively.

while Lee, M.J. (2011) developed another relation illustrating the trend between q_c and σ'_v based on some high accurate field and laboratory simulations for the CPT as shown in Figure 1. Also Lee, M.J. (2011) included the effect of D_r as illustrated in Figure 2 to q_c and σ'_v.

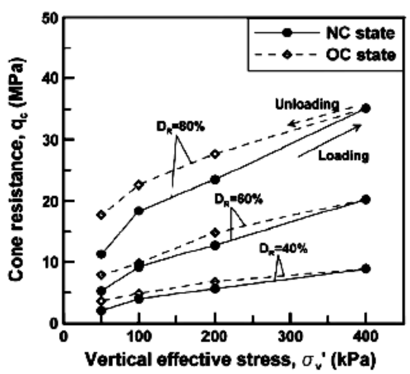

Figure 1. q_c vs σ'_v relationship. (after Lee (2011))

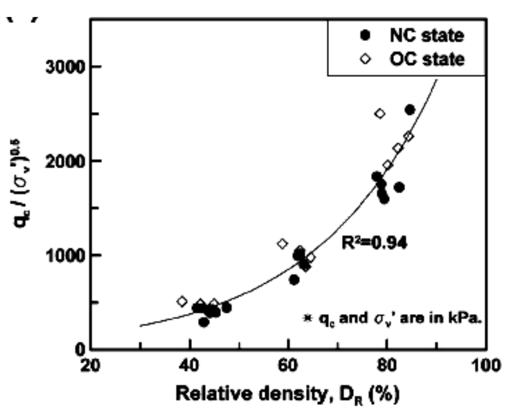

Figure 2. q_c, D_r, and σ'_v relationship. (after Lee (2011))

Also it is worthy to mention that Robertson and Wride (1998 and 2000) and Wride et al . (2000) stated some important correlations for the truly normalized cone penetration resistance for overburden stress (q_{c1N}) which is dimensionless; as follows:

$$q_{c1} = q_c C_Q \qquad [4]$$

where q_{c1} is the tip resistance normalized for the overburden stress (100 kPa), and C_Q can be estimated as follow:

$$C_Q = \left(\frac{P_a}{\sigma'_{v0}}\right)^{0.5} \le 2 \qquad [5]$$

Hence;

$$q_{c1N} = \left(\frac{q_c}{P_{a2}}\right) C_Q = \left(\frac{q_{c1}}{P_{a2}}\right) \qquad [6]$$

where P_{a2} is also equal to 100 kPa but it must be substituted in q_c units.

Schmertmann's (1978) figured a relation between the tip resistance q_c and σ'_v at various D_r values as shown in Figure 3 and then some correlations with Figure 4 were carried out to take into account the effect off over consolidation as shown in equations 7, and 8

$$q_{cOC} / q_{cNC} = 1 + 3/4\left(\frac{K'_{oOC}}{K'_{oNC}} - 1\right) \qquad [7]$$

$$\frac{K'_{oOC}}{K'_{oNC}} = \left(OCR\right)^{0.42} \qquad [8]$$

where:
q_{cOC} and q_{cNC} represent the tip resistances for over consolidated and normally consolidated sands respectively. Also K'_{oOC} and K'_{oNC} represent the coefficients of earth pressures at rest for over consolidated and normally consolidated sands respectively.

On the other hand Salgado et al., 1997. presented some correlations for the effects of σ'_v and σ'_h on the normalized CPT tip resistance in comparison with some earlier studies as follow:

$$q_{c1k0,NC} = C_{NV} C_{NH} q_c \qquad [9]$$

where:
$q_{c1k0,NC}$ and q_c are the normalized and recorded tip resistances respectively.
C_{NV} was suggested by Liao and Whitman (1986), as follows:

$$C_{NV} = \sqrt{\frac{P_a}{\sigma'_v}} \qquad [10]$$

Salgado et al., 1997 verified the previous mentioned relation at D_r = 0.50 and generally presented C_{NV} - σ'v relations at several D_r values as in Figures 5 and 6. Also C_{NH} was stated in accordance with allot of researches e.g. Baldi et al. (1982, 1985) as in Equation 11, and generalized by Salgado et al., 1997 in Figure 6.

$$C_{NH} = \sqrt{\frac{K_{0,NC}}{K_0}} \qquad [11]$$

where:

$K_{0,NC}$ is the coefficient of earth pressure equivalent to $q_{c1k0,NC}$ and K_0 is the coefficient of earth pressure for normally consolidated soils.

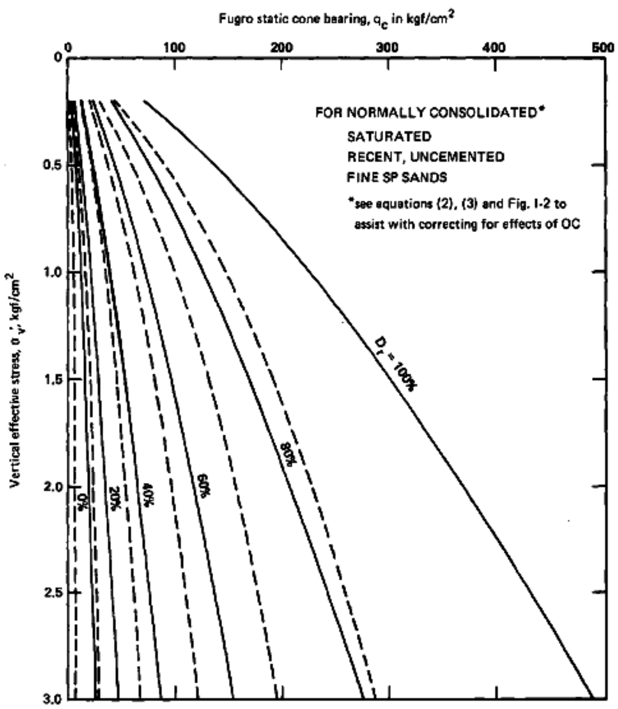

Figure 3. q_c - σ'_v relationship for various D_r values. (after Schmertmann's (1978))

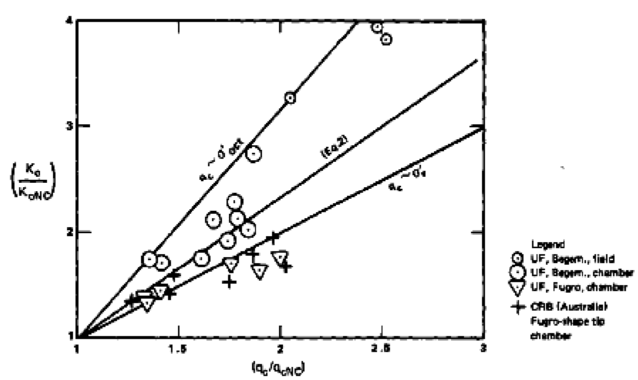

Figure 4. Normalized tip resistance to normalized K for some field and champer tests (after Schmertmann's (1978)).

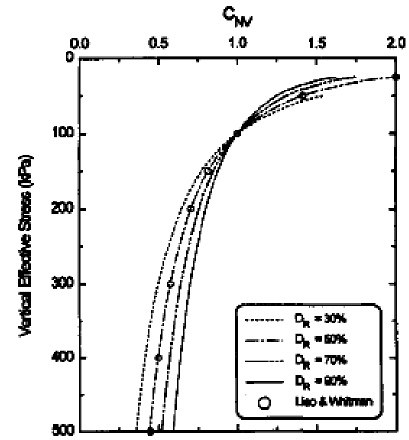

Figure 5. C_{NV} vs σ'_v relationship obtained using CONPOINT with expression of Liao and Whitman, 1985 (after Salgado et al. (1997)).

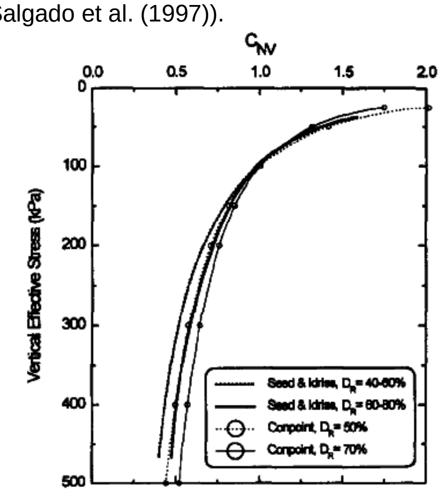

Figure 6. C_{NV} vs σ'_v relationship obtained using CONPOINT with values recommended by Seed and Idriss, 1971 (after Salgado et al. (1997)).

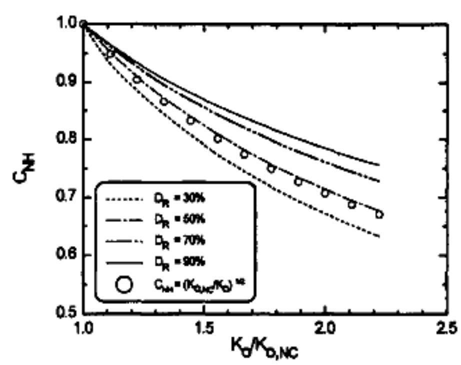

Figure 6. C_{NH} vs K_0/ $K_{0,NC}$ relationship (after Salgado et al. (1997)).

3 EXPERIMENTAL WORK

An objective was set, from a series of experimental simulations for the CPT on natural disturbed sand samples as well as artificial (glass beads) representing sand sizes, to justify and develop new equations governing the relations between (q_c) and (f_s) values and the previously discussed geotechnical parameters.

3.1 Testing Assembly and Samples:

An assembly developed earlier in the geotechnical laboratory at Sherbrooke University (Ghali, et al., 2014) has been used to simulate Laboratory CPTs.This assembly as shown in Figure 7 consists of loading arm, guide frame, fully confined cell with several inner semi-flexible walls, lateral and vertical pressure. Simply as illustrated in the above mentioned figures, the loading arm works as an oedometer with arm ratio of 5.45 and own weight reaction of 1.875 kN on the top surface of the samples. Vertical loads applied at the end of the loading arm by a calibrated hydraulic compressor and the applied loads were monitored instantly during all tests. the total vertical stresses were calculated and verified using pressure sensor was put at the bottom of the cell. Several artificial and natural soil samples were prepared in the cell (340 mm inner diameter and 500 mm height) shown in Figure 8.

3.2 Testing Program and Results:

Several tests were carried out on glass beads samples and some corresponding natural clean sand soil samples (previously prepared and tested by Ghali et al, 2014) as illustrated in Table 1 and Figure 9, under certain given initial relative densities, specific gravity, dry densities, initial volume, and known volumetric changes during testing. The maximun void ratios (e_{max}) and the minimum void ratios (e_{min}) were also determined for all tested samples as presented in Tables 2a and 2b, respectively. Figure 10 shows a sample of the angularity of a used sand particles.

Table 1. Samples coding numbers (After Ghali et al., 2014).

Sample No.		D_{50} (mm) 0.50	1.00	2.00	3.00	4.00
C_u	2.5	A-1	A-2	A-3	A-4	A-5
	4	B-1	B-2	B-3	B-4	B-5
	8	C-1	C-2	C-3	C-4	C-5
	12.5	D-1	D-2	D-3	D-4	D-5

Table 2a. Maximum void ratio for glass beads(After Ghali et al., 2014).

Sample No.		D_{50} (mm) 0.50	1.00	2.00	3.00	4.00
C_u	2.5	0.61	0.56	0.53	0.51	0.50
	4	0.51	0.47	0.44	0.42	0.40
	8	0.43	0.39	0.37	0.36	0.35
	12.5	0.42	0.39	0.36	0.33	0.33

Table 2b. Minimum void ratio for glass beads (After Ghali et al., 2014).

Sample No.		D_{50} (mm) 0.50	1.00	2.00	3.00	4.00
C_u	2.5	0.45	0.42	0.40	0.39	0.39
	4	0.38	0.35	0.33	0.31	0.30
	8	0.32	0.30	0.29	0.27	0.27
	12.5	0.32	0.30	0.28	0.26	0.26

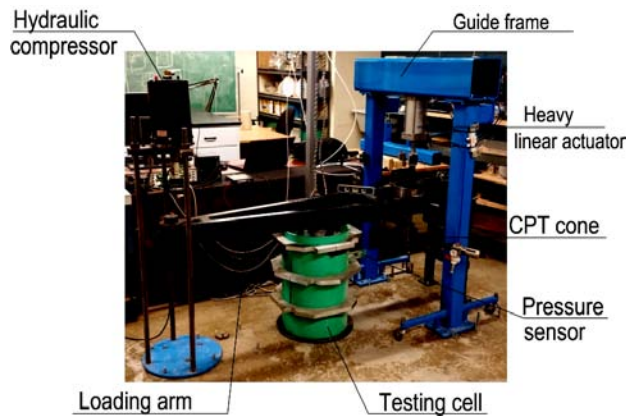

Figure 7. The assembly used to simulate the CPT.

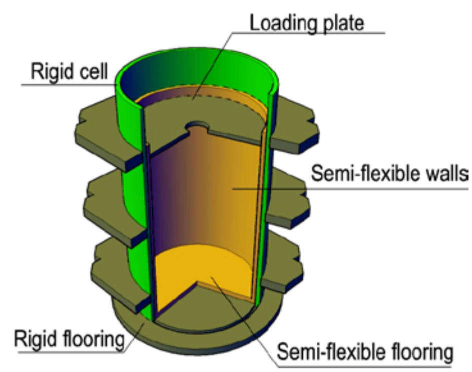

Figure 8. Testing cell equipped by several horizontal and vertical pressure sensors.

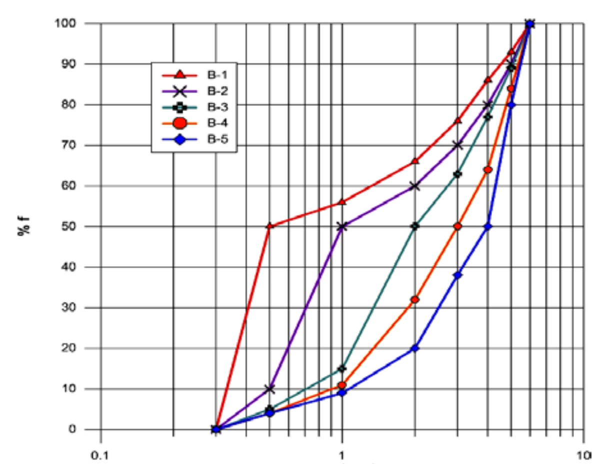

Figure 9. Sample for the tested glass beads gradation: C_u = 4 (After Ghali et al., 2014).

Figure 10. Sample for clean tested sand of average angularity (A_{2D}) = 650.

The cone tip resistances (q_c) and the sleeve friction resistances (f_s) were recorded among all tests under several applied effective overburden pressures as well as different lateral pressures, sample of the results are illustrated in Figures 11a-11d.

Also several tests were carried out under effective overburden pressure of 98 kPa and different coefficient of lateral pressures, and tri-axial tests were performed for all the tested samples in order to obtain the internal friction (ϕ'). Equation 12 is used to calculate the coefficient of lateral earth pressure at rest (K_{0NC}), hence the normalized (q_{c1}) and (f_{s1}) at (σ'_v = 98 kPa) can be obtained for each individual test as shown in Figure 12.

$$K_{0NC} = 1 - \sin\phi' \qquad [12]$$

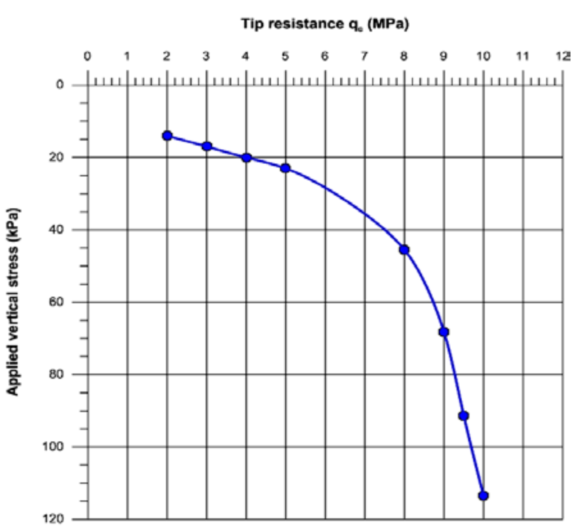

Figure 11a. Sample schematic curve for the relation between (q_c) and the effective overburden stress.

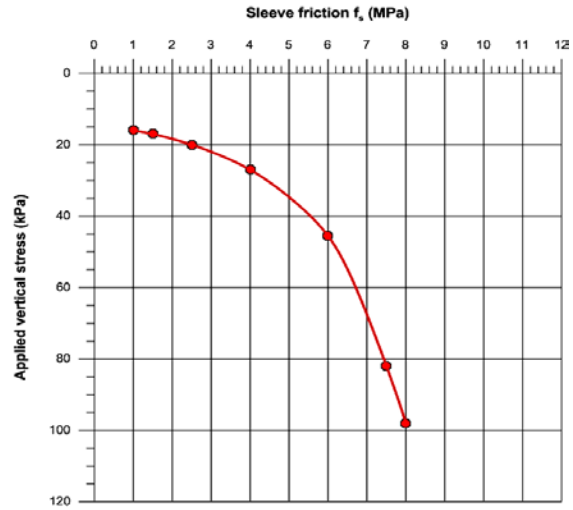

Figure 11b. Sample schematic curve for the relation between (f_s) and the effective overburden stress.

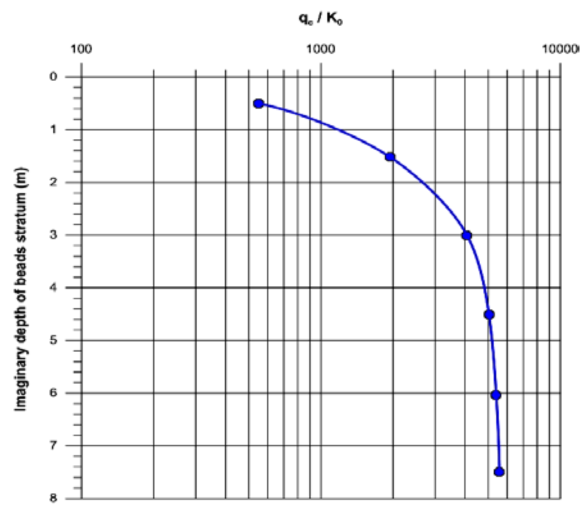

Figure 11c. Sample schematic curve for the variation of (q_c /K_0) with depth.

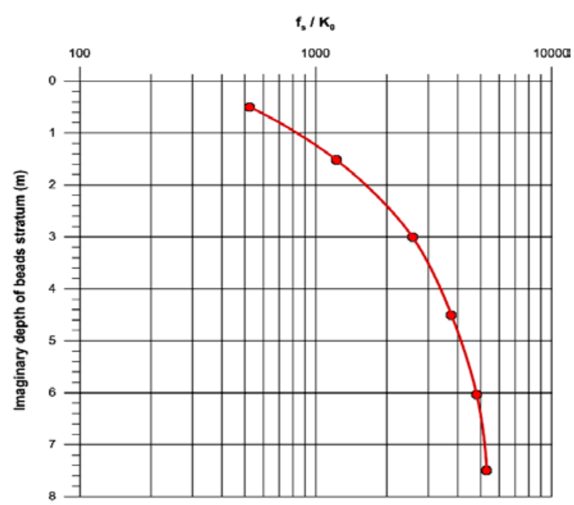

Figure 11d. Sample schematic curve for the variation of (f_s /K_0) with depth.

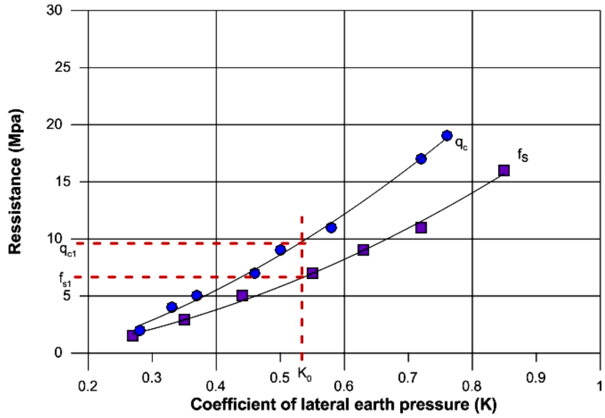

Figure 12. Example for predicting (q_{c1}) and (f_{s1}) at (σ'_v = 98 kPa) for each individual test.

4 ANALYSIS OF RESULTS AND PROPOSED RELATIONS

The relation between (D_{50}, A_{2D} and C_u) and the void ratio range were presented earlier by Ghali et al., 2014 in Equation 13 as a best fitting for the relations Figure 13.

$$e_{max} - e_{min} = \frac{0.06 * D_{50}^{(0.046 \log C_u - 0.17)}}{e^{\frac{-A_{2D}}{1000}} * \log(D_{50}+1) * C_u^{0.285}} \quad [13]$$

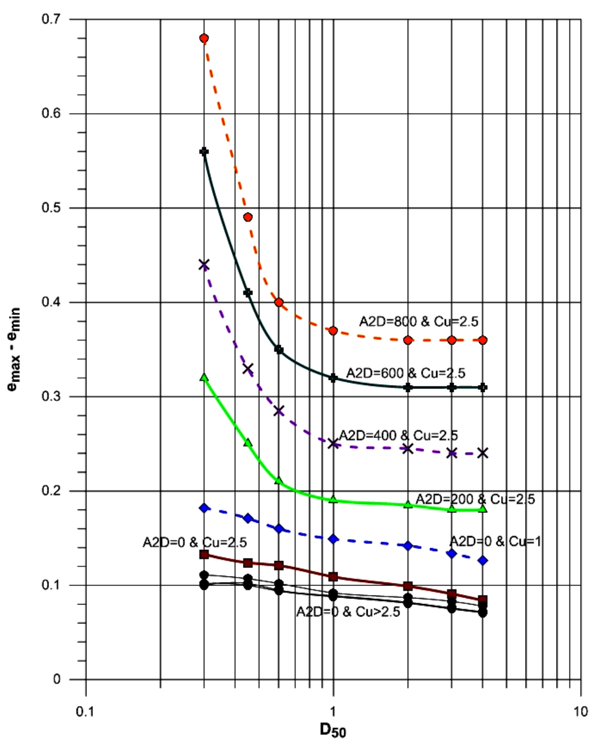

Figure 13. Sample of the present database for the effect of D_{50}, C_u and A_{2D} on (e_{max} - e_{min}) (after Ghali et al., 2014).

While the effect of the void ratio range on the normalized tip resistance and the normalized sleeve friction for the tested clean sands as well as spherical glass beads were presented in Figures 14a, & 14b.

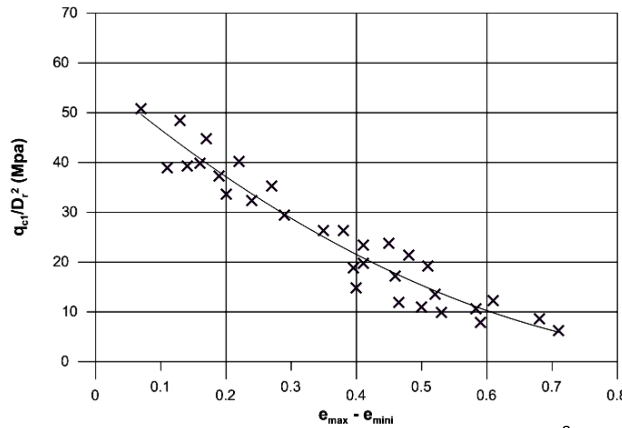

Figure 14a. Proposed correlation between (q_{c1} / D_r^2) and void ratio range.

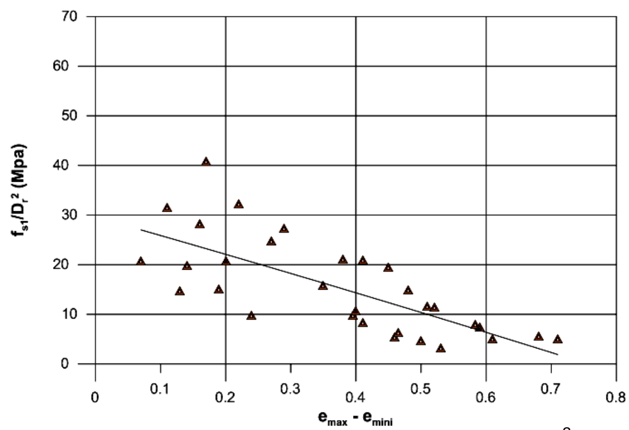

Figure 14b. Proposed correlation between (f_{s1} / D_r^2) and void ratio range.

On the other hand several tests were carried out under $\sigma'v$ = 98 kPa and several lateral pressures, in order to predict the effect of mean confinement pressure on the normalized q_c and f_s values as shown in:

$$\frac{q_c}{q_{c0}} = \left(\frac{1+2K}{1+2K_0}\right)^{x1} \quad [14]$$

and

$$\frac{f_s}{f_{s0}} = \left(\frac{1+2K}{1+2K_0}\right)^{x2} \quad [15]$$

where q_{c0} and f_{s0} are the tip resistance and sleeve friction at K=K_0 respectively, and x1 & x2 are constants.

New proposed relation was preliminarily developed to predict the effect of each individual parameter included in the present study on the CPT tip resistance values as follows:

$$q_c - f_{(q_0)} = f_{q(D,U,A)}.f_{q(N,OCR)}.D_r^{\,2} \qquad [16]$$

where

$f_{(q_0)}$ is a function representing the CPT tip resistance values for the soil at loosest state (D_r = 0.0), which is very small value ≈ 0.0.

and

$f_{q(D,U,A)}$ is a function of D_{50}, A_{2D} and C_u, developed under σ'v = 98 kPa and K = K_0 as follows:

$f_{q(N,OCR)}$ is a function of ϭ'v and OCR. as follows:

$$f_{q(N,OCR)} = \left(\frac{1+2K}{1+2K_0}\right)^{x1} * \left(\frac{\sigma' v}{98}\right)^{0.5} \qquad [17]$$

On the other hand the preliminary proposed relations for the sleeve friction can be summarized as follow:

$$f_s - f_{(f_0)} = f_{f(D,U,A)}.f_{f(N,OCR)}.D_r^{\,2} \qquad [18]$$

where

$f_{(f_0)}$ is a function representing the CPT sleeve friction values for the soil at loosest state (D_r = 0.0), which is very small value ≈ 0.0.

and

$f_{f(D,U,A)}$ is a function of D_{50}, A_{2D} and C_u, developed under σ'v = 98 kPa and K = K_0 as follows:

$f_{f(N,OCR)}$ is a function of ϭ'v and OCR. as follows:

$$f_{f(N,OCR)} = \left(\frac{1+2K}{1+2K_0}\right)^{x2} * \left(\frac{\sigma' v}{98}\right)^{0.5} \qquad [19]$$

5 RELIABILITY OF THE PRESENT CORRELATION

Results were found to be matching with existing field tests with very small deviation which may be due to:

a) The presence of fine grained soil content and water content which are not included in this study.

b) Neglecting the effect of surface roughness of coarse grained particles.

6 CONCLUSIONS

Based on the preliminary data collected and analyzed from the present experimental simulations, new correlations were developed to give reliable relations between (q_c and f_s) values and (D_r, ϭ'v, void ratio range, D_{50}, C_u, $ϭ'_m$, OCR and angularity). The key finding of this study can be summarized as follows:

a) (q_c and f_s) values were verified to be proportional with the square of the relative density.

b) (q_c and f_s) values were verified to be proportional with $(ϭ'v/98)^{0.50}$ where ϭ'v in kPa.

c) (q_c) values were found to be related with the OCR as well as the mean confinement pressure by the relation $((1+2k)/(1+2k_0))^{x1}$.

d) (f_s) values were found to be related with the OCR as well as the mean confinement pressure by the relation $((1+2k)/(1+2k_0))^{x2}$.

e) The effect of angularity on (q_c and f_s) values decreases with the increase of D_{50}.

REFERENCES

Baldi, G., Bellotti, R., Ghionna, V" Jamiolkowski, M., and Pasqualini, E. (1982). "Design parameters for sands from CPT." *Proc., 2nd Eur. Symp. on Penetration Testing, A. A. Balkema, Rotterdam, The Netherlands*. Vol. 2, 425-432.

Baldi, et a!. (I985). "Laboratory validation of in-situ tests." *Italian Geo- tech. Assoc. (AGI) Jubilee Vol., Proc., 11th Int. Conf. on Soil Mech. and Found. Engrg., A. A. Balkema, Rotterdam, The Netherlands*.

Baldi, G., Bellotti, R., Ghionna, V" Jamiolkowski, M., and Pasqualini, E. (1986). "Interpretation of CPT's and CPTU's. 2nd Part: drained penetration on sands." *Proc., 4th Int. Geotech. Seminar: Field Instrumentation and In Situ Measurements, Nanyang Technol. Univ" Singapore*. 143-162.

Ghali M., Hussien M. N., Karray M., Chekirad M., & Roubtsova V. 2014. "Laboratory investigation on the effect of grain size distribution of granular material on penetration test results". *67th Canadian Geotechnical Society (CGS) conference, , Regina; October 2014*, Paper NO. 306.

Kulhawy, F. H., and Mayne, P. W., 1990. Manual on Estimating Soil Properties for Foundation Design, *Final Report 1493-6, EL-6800, Electric Power Research Institute, Palo Alto, CA*.

Kulhawy, F.H. and Mayne, P.W., 1991. " Relative density, SPT and CPT interrelationships", in: *Proc. Ist Int. Symp. on Calibration Chamber Testing, New York*, pp. 197–211.

Lee, M.J. et al., 2011. Effect of stress history on CPT and DMT results in sand. *ELSEVIER, Engineering Geology*, vol 117, pp 259-265.

Liao, S.C., and Whitman, R.V. 1986. Overburden correction factors for SPT in sand. *Journal of Geotechnical Engineering Division, ASCE*, 112(3): 373 - 377.

Robertson, P. K., and Campanella. R. G. 1983. "Interpretation of cone penetration tests. Part I: Sand." *Can. Geotech. 1., Ottawa, Canada*. 20. 718-733.

Robertson, P. K., and Campanella. R. G., and Wightman A., 1983. "SPT-CPT correlations". *ASCE Journal of Geotechnical and Geonvironmental Engineering*, 109(11): 1449-1459.

Robertson, P.K., Campanella, R.G., Gillespie, D. and Greig, J. 1986." Use of piezometer cone data". *Proceedings of the ASCE Specialty Conference In Situ '86: Use of In Situ Tests in Geotechnical Engineering, Blacksburg*, pp.1263-80.

Robertson, P.K., and Wride, C.E. (Fear) 1998. "Evaluating cyclic liquefaction potential using the cone penetration test". *Canadian Geotechnical Journal*, 35(3): 442–459.

Robertson, P.K., Wride, C.E. (Fear), List, B.R., Atukorala, U., Biggar, K.W., Byrne, P.M., et al. 2000." The CANLEX project: summary and conclusions". *Canadian Geotechnical Journal*, 37(3): 563–591.

Salgado, R., Boulanger, R.W., and Mitchell, J.K. 1997. Lateral stress effects on CPT liquefaction resistance correlations. *ASCE Journal of Geotechnical and Geonvironmental Engineering*, 123(8): 726 - 735.

Salgado, R., Mitchell, J.K., and Jamiolkowski, M. 1997. "Cavity expansion and penetration resistance in sands". *ASCE Journal of Geotechnical and Geonvironmental Engineering*, 123(4): 344 - 354.

Seed, H.B., and Idris, I.M., (1971). "Simplified procedures for evaluating soil liquefaction potential". *J. of Mech. and Found. Dev., ASCE*, 97(9), 1249-1273.

Schmcrtmann, J. H. (1978). "Guidelines for cone penetration test, performance and design." *Rep. FHwA-TS-78-209, Fed. Hwy. Admin. (FHwA), Washington. D.C.*

Tran, C. 2005. "Truth: non-additive measures for the determination of relative density of sands using CPT measurements". *ELSEVIER C. R. Mecanique*, 333: 605-611

Wride, C.E. (Fear), Robertson, P.K., Biggar, K.W., Campanella, R.G., Hofmann, B.A., Hughes, J.M.O., Kupper, A., and Woeller, D.J. 2000. "Interpretation of in situ test results from the CANLEX sites". *Canadian Geotechnical Journal*, 37(3): 505–529.