K_0 determination of Sand Using CPT Calibration Chamber

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ABSTRACT: It is always an interest in geotechnical engineering to determine the coefficient of at rest pressure (K_0) in soils without the need of sampling. This is especially true for cohesionless soils. Many attempts have been made in the past to determine the coefficient of at rest pressure (K_0) using in-situ test results such as pressuremeter test, blade test, and cone penetration test (CPT) to name a few.

In this paper, a wide database of CPT test in calibration chambers has been used to propose a relationship between cone tip resistance and in-situ horizontal stress. This relationship is compared to two other relationships developed previously by previous researchers. The comparison shows that the proposed equation predicts the in-situ horizontal stress with better agreement.

1 INTRODUCTION

In order to control the stability and perform a stress-deformation analysis of a geotechnical system, it is essential to know the in-situ stress state of the ground. The in-situ vertical stress can be simply calculated if the depth and the soil density are known. However, it is more complicated to calculate the in-situ horizontal stress, since it depends on several other soil characteristics, such as stress history and overconsolidation history. It has always been one of the most challenging and yet interesting geotechnical problems to obtain the coefficient of at-rest earth pressure by means of in-situ or laboratory tests and thus, there have been many attempts devoted to provide a reliable method to do so (e.g. Jefferies et al. 1987, Houlsby & Hitchman 1988, Masood & Mitchell 1993, Jamiolkowski et al. 2003).

Obtaining undisturbed samples of cohesionless soils is very difficult, and it is sometimes practically impossible. Therefore there has always been an inclination toward determination of major characteristics of sandy soils using in-situ tests. The Cone Penetration Test (CPT) has proved to be one of the best in-situ tests for providing mechanical properties of soil. Different equations have been provided to relate CPT results with different soil characteristics such as soil friction angle, relative density, and elastic modulus (Robertson & Campanella 1983, Baldi et al. 1986). Moreover, there have been some efforts to relate CPT tip resistance to in-situ horizontal stress.

To develop reliable relationships between CPT results and soil properties, the test should be performed in a sample whose characteristics are well known. Therefore calibration chambers have been designed and constructed so that the initial soil properties and calibration chamber boundary conditions are well defined. Using CPT results, it may be possible to find several relationships between soil properties and CPT results. During the last decades, CPT calibration chambers have been widely used. A list of calibration chambers in the world was provided by Ghionna & Jamiolkowski (1991).

It is shown in this paper that in-situ horizontal stress and sand relative density are the most influential parameters on cone tip resistance. In this regard, a new relationship between cone tip resistance, horizontal stress and sand relative density is proposed. The proposed relationship is compared to two other relationships suggested by previous researchers. The proposed new relationship is proved to be in better agreement with test results.

2 DATABASE

The database consists of 631 CPT test data gathered from four different calibration chamber test sources: Baldi et al. (1986), Salgado (1993), Lunne et al. (1997), and Houlsby & Hitchman (1988). The database consists of several sand initial parameters such as dry density, relative density, stress state expressed as vertical and horizontal stress or vertical stress and coefficient of lateral earth pressure at rest, overconsolidation ratio, and constrained modulus. The database also consists of chamber to probe diameter ratio (R_D) for each test, and the measured results (cone tip resistance and sleeve friction).

Four different boundary conditions are employed in calibration chambers, as described in Table 1. The number and percentage of tests performed under different boundary conditions are presented in the last two columns of Table 1.

Table 1. Definition of calibration chamber boundary conditions

Boundary Condition Type	Vertical Status	Horizontal Status	No. of tests	Percentage (%)
BC1	σ_v = Constant	σ_h = Constant	417	66.1
BC2	$\varepsilon_v = 0$	$\varepsilon_h = 0$	27	4.3
BC3	σ_v = Constant	$\varepsilon_h = 0$	139	22.0
BC4	$\varepsilon_v = 0$	σ_h = Constant	48	7.6

The database consists of five sand types: Ticino, Hokksund, Toyoura, Monterey and Leighton Buzzard. Table 2 presents the number and percentage of tests performed on each sand type.

Table 2. Number and percentage of tests performed on each sand type

Sand Type	No. of tests	Percentage (%)
Ticino	340	53.9
Hokksund	102	16.2
Toyoura	71	11.3
Monterey	61	9.7
Leighton Buzzard	57	9.0

3 CONE TIP RESISTANCE VERSUS HORIZONTAL STRESS

Figures 1-3 show relationships between cone tip resistance and initial horizontal stress for several series of tests performed in the chamber. Figure 1 shows two sets of data obtained from CPT tests in BC1 type calibration chamber. The vertical stress for both sets is identical, and it is equal to 110 kPa. However, the relative density for one set is 80%, and for the other is 90%. Figures 1-3 show that the trends of both sets are similar, and that cone tip resistance (q_c) increases as initial horizontal stress (σ_h) increases.

Figure 2 shows the effect of horizontal stress on the calibration chamber test results of cone tip resistance more clearly. The initial conditions consist of: BC1 chamber boundary condition, vertical stress of 110 kPa, and relative densities of 40%, 60% and 80%. The data are divided into three groups according to their relative density. Similar to Figure 1, the trends of all three sets of data show that the cone tip resistance increases as horizontal stress increases.

The sample data presented in Figure 3 have been tested under conditions of BC4 boundary condition and vertical stress of 110 kPa. In Figure 3, the data sets with relative densities of 50%, 70% and 90% are presented. Similar to Figures 1 and 2, Figure 3 also implies that cone tip resistance increases as horizontal stress increases.

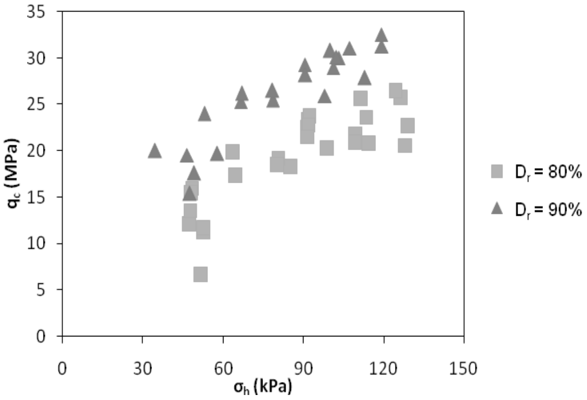


Figure 1 - Effect of relative density on cone tip resistance, BC1, σ'_v = 110 kPa, R_D = 34, Ticino sand

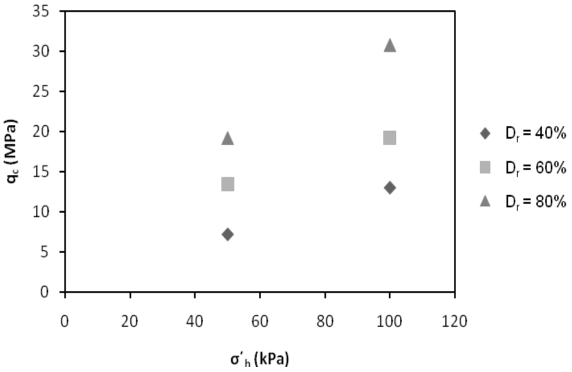


Figure 2 - Effect of relative density on cone tip resistance, BC1, σ'_v = 110 kPa, R_D = 30, Monterey sand

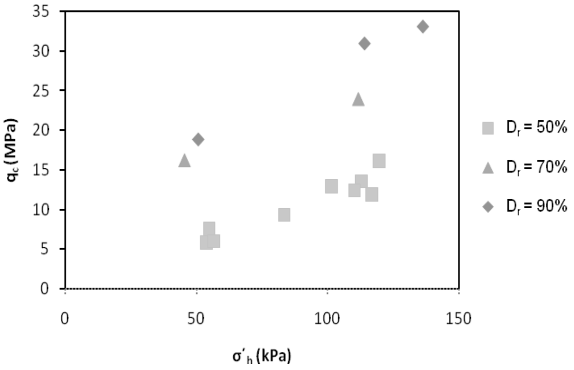


Figure 3 - Effect of relative density on cone tip resistance, BC4, σ'_v = 110 kPa, R_D = 34, Ticino sand

Considering Figures 1-3, it can be concluded that horizontal stress has a profound effect on cone tip resistance values. This has also been shown by Baldi et al. (1986), Houlsby & Hitchman (1988), Salgado (1993), Ahmadi et al. (2005), and most recently by Karambakhsh (2008).

However, the trends of data points indicate that the sand relative density also has a significant effect on cone tip resistance measurements. In all of these figures, it could be observed that for the same horizontal stress, higher relative density values results in higher cone tip resistance values. Therefore it may be possible to relate cone tip resistance with relative density. This is investigated in the following section.

4 EFFECT OF RELATIVE DENSITY

Figures 4 and 5 illustrate the effect of relative density on cone tip resistance. In Figure 4 two sets of data are chosen. Vertical stress for both sets is 200 kPa, and the tests were performed in a BC1 type chamber. Horizontal stress for one set is 65 kPa and for the other 105 kPa. The trends of both sets show that cone tip resistance increases as relative density increases. Also Figures 4 and 5 show that, for a constant relative density, larger horizontal stress leads to larger cone tip resistance values.

Figure 5 shows the cone tip resistance values versus relative density for a set of data having horizontal stress of 50 kPa and vertical stress of 110 kPa. All data points are for CPT test in a BC3 calibration chamber. Figure 5 also indicates that, besides horizontal stress, the cone tip resistance is a function of relative density as well. .

This conclusion is consistent with many other previous studies, such as Schmertmann (1976), Baldi et al. (1986), Houlsby & Hitchman (1988), Jamiolkowski et al. (2003).

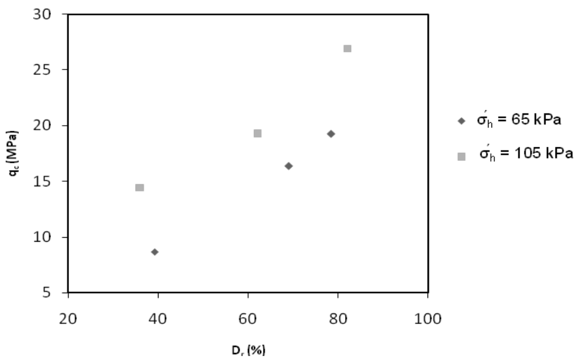


Figure 4 – Effect of relative density and stress on cone tip resistance, BC1, $\sigma'_v = 200$ kPa, $R_D = 21$, Monterey sand

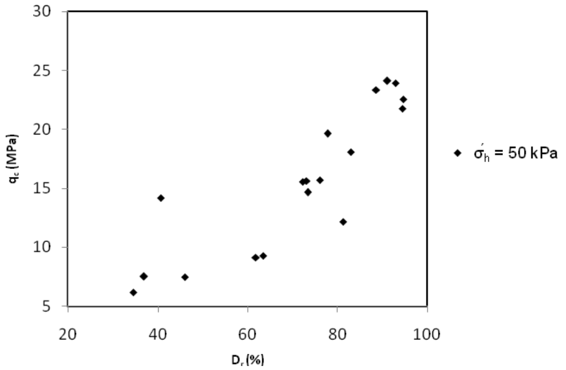


Figure 5 - Effect of relative density and stress on cone tip resistance, BC3, $\sigma'_v = 110$ kPa, $R_D = 34$, Ticino sand

5 PROPOSED NEW RELATIONSHIP

It is shown that the cone tip resistance is a function of horizontal stress and sand relative density. Below, a relationship is proposed that predicts cone tip resistance using relative density and horizontal stress (Equation 1). If such relationship is available, it is possible to determine the initial horizontal stress using cone tip resistance and relative density.

$$q_c = C_0 \, P_a \left(\frac{\sigma'_h}{P_a} \right)^{C_1} D_r^{\,C_2} \qquad (1)$$

In Equation 1, q_c = cone tip resistance, P_a = reference pressure or atmosphere pressure in the units of choice, 98.1 kPa (1 kg/cm^2) σ'_h = initial effective lateral stress before penetration, D_r = relative density (in decimal), C_1 , C_2 = empirical constants.

Table 3 shows the values for C_1 and C_2 parameters in Equation 1, which are determined based on a simple statistical procedure. The regression values (R^2) and the per cent error are also included in Table 3. Table 3 shows that for each boundary condition type, different C_1 and C_2 values are obtained which result in the lowest regression value. Nevertheless, it would be more practical if C_1 and C_2 values for any type of boundary condition be the same.

Table 3- The magnitude of constants of equation 1 for different boundary conditions

	BC1	BC2	BC3	BC4	Total
C_0	350	320	370	320	360
C_1	0.50	0.24	0.45	0.48	0.5
C_2	1.51	1.10	1.51	1.29	1.50
R^2	0.85	0.95	0.84	0.91	0.84
Error $[(\lvert q_{c,predicted}-q_{c,measured}\rvert)/q_{c,measured}]\times100\%$	23	18	25	14	22

Thus, it is suggested to use a general form for the proposed relationship with C_0 = 360, C_1 = 0.5, and C_2 = 1.5. The general form of the relationship is shown in Equation 2, and its consistency with database is shown in Table 4.

$$q_c = 360\, P_a \left(\frac{\sigma'_h}{P_a}\right)^{0.5} D_r^{\,1.5} \qquad (2)$$

Table 4- Consistency of Equation 2 with database

	BC1	BC2	BC3	BC4	Total
R^2	0.85	0.92	0.84	0.91	0.84
Error $[(\lvert q_{c,predicted}-q_{c,measured}\rvert)/q_{c,measured}]\times100\%$	27	14	23	17	27

Equation 2 can now be manipulated to develop a relationship to determine horizontal stress from cone tip resistance:

$$\sigma'_h = \frac{q_c^2}{360^2\, P_a\, D_r^3} \qquad (3)$$

Equation 3 suggests that if cone tip resistance and sand relative density are known, it would be possible to determine the in-situ horizontal stress. However, it should be mentioned that the determination of sand relative density may not be straightforward. The proposed new relationship [Equation 2] is now compared to other relationships proposed by other researchers. Many relationships have been proposed to predict cone tip resistance (Schmertmann 1976, Baldi et al. 1986, Houlsby & Hitchman 1988, Houlsby 1998, Jamiolkowski et al. 2003). For example Jamiolkowski et al. (2003), using the form of proposed equation of Schmertmann (1976), developed an equation as follows:

$$q_c = C_0 P_a \left(\frac{\sigma'_m}{P_a}\right)^{C_1} \exp(C_2 D_r) \qquad (4)$$

In this equation, σ'_m is the mean effective stress and the magnitude of C_0, C_1 and C_2 are 24.94, 0.46 and 2.96 respectively.

Houlsby 1998 proposed another relationship based on effective horizontal stress and relative density:

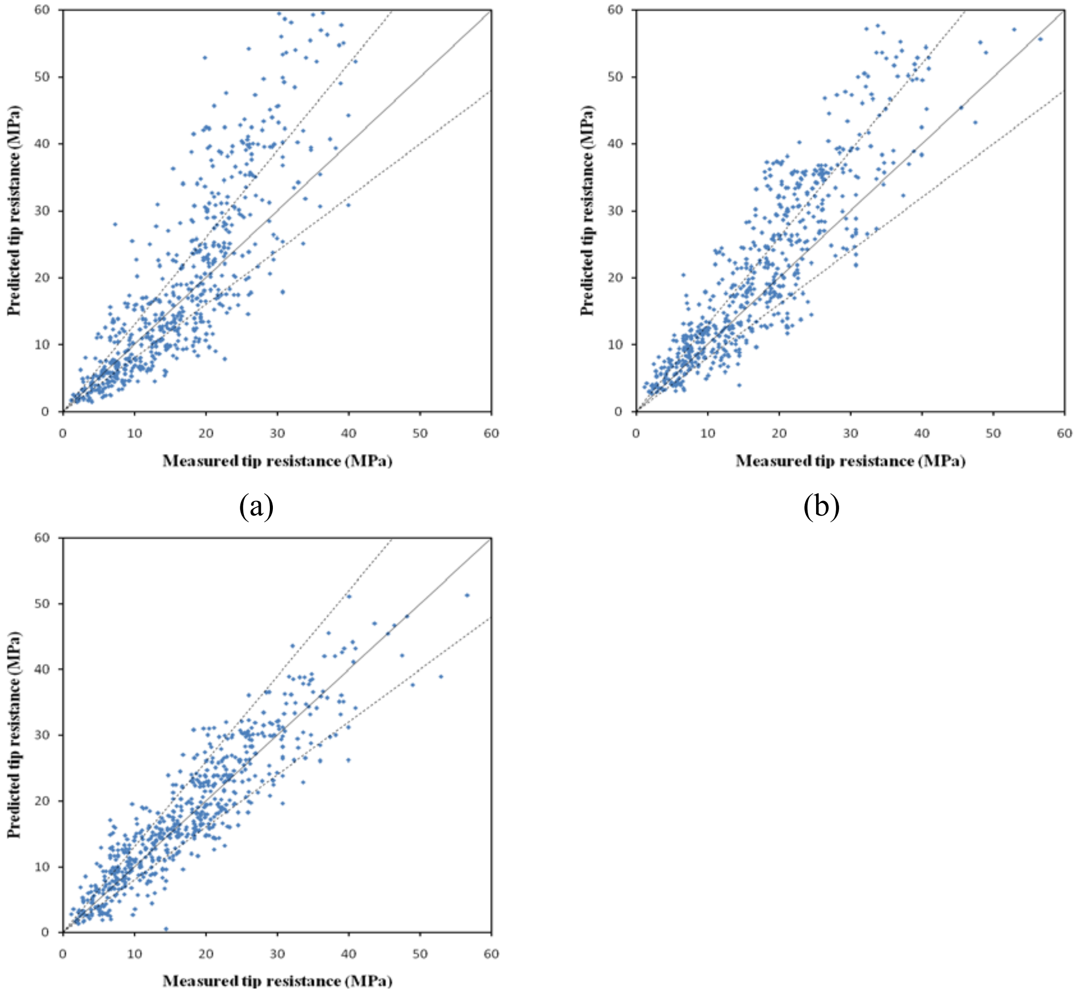
$$\log_{10}\left(\frac{q_c - \sigma_h}{\sigma'_h}\right) = 1.51 + 1.23\, D_r \qquad (5)$$

In which σ_h = horizontal stress, σ'_h = effective horizontal stress and D_r = relative density.

The proposed new relationship (Equation 2) is now compared to other relations (Equation 4 and Equation 5). In order to do so, all equations are applied to the data gathered in the database.

Figure 6a shows the predicted values of cone tip resistance versus measured ones for all the data points considered in this study using Equation 5 (Houlsby (1998) approach). The error band of ±30% is also shown in Figure 6a. It is shown that many of the data points are out of the band. It can also be concluded by this figure that Equation 5 overestimates cone tip resistance since most of the data are above the 45^0 line (which indicates complete consistency between predicted and measured cone tip resistances).

Figure 6b is based on the relationship proposed by Jamiolkowski et al. (2003) and shows that most of data points are above the 45^0 line. This means that Equation 4 also overestimates cone tip resistance. In addition it is shown that there are many data points outside the ±30% band.



(a)

(b)

(c)

Figure 6a - Agreement between predicted and measured values of cone tip resistance using: (a)Equation 5, (b) Equation 4, (c) Equation 2 (this study). Broken lines indicate difference between predicted and measured tip resistance value of 30%.

In Figure 6c, Equation 2 which is proposed in this paper is applied to the sample data of the database. This figure indicates that the majority of data points are close to the 45^0 line, which indicates that Equation 2 favorably predicts cone tip resistance.

Comparison of Figures 6a-c indicates that Equation 2 is more consistent with the experimental data because more data points are close to the 45^0 line.

Furthermore Figures 6a-c indicate that Equation 2 predicts cone tip resistance better than the other two since Figure 6c shows less scatter in contrast to Figures 6a,b because most of the points are among the bounds of ± 30%.

Considering these results, it can be concluded that proposed equation by this study can predict cone tip resistance very well. Therefore, it can be used to determine lateral stress from cone tip resistance and relative density.

6 CONCLUSION

A database of calibration chamber CPT results in sands has been reviewed and shows that the cone tip resistance is controlled primarily by the sand relative density and the in-situ horizontal effective stress (equation 2).

A general relationship has been proposed and has been compared with two other available relationships. The result indicates that equation 2 suggested in this study can predict cone tip resistance better than other available relationships.

Thus horizontal geostatic stress can be estimated from the results of CPT if the relative density of the soil is known.

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