JKAU: Eng. Sci., Vol. 2, pp. 19-33 (1410 A.H. / 1990 A.D.)

Density Prediction Using a Static Cone Penetrometer*

ZAKI A. BAGHDADI, FOUAD M. GHAZALI AND AHMED M. KHAN
Civil Engineering Department, Faculty of Engineering,
King Abdulaziz University, Jeddah.

ABSTRACT. This paper presents results of investigation on the use of a static cone penetrometer for predicting densities of two air dry granular soils. Cone penetration resistance values (q_c) were measured for soil specimens prepared at specific densities with different surcharge loads. Linear regression techniques were utilized to develop correlations between values of (q_c), surcharge loads and depths of penetration. Calibration curves to be used for predicting densities are given on the basis of tests data. A procedure is outlined for use of the penetrometer in determining soil densities.

(Keywords: Compaction, Density, Sands, Static Penetration Test)

Introduction

As indicated by Van de Graaf and Zuidberg[1], probably the best known product of Dutch geotechnology is the cone penetrometer which is still in use today.

Cones are still a subject of research and as emphasized by Verruijt, *et al.*[2] at the second European Symposium on Penetration Testing, effort is being made to calibrate cone data against other soil parameters.

The use of static cone penetrometer in measuring density of cohesionless soils in the field and in the laboratory is considered to be a recent method in which its main application is concentrated in the quality control of compaction of man-made fills, bases and sub-bases of roads, and densification of natural soils.

Cohesionless soils cannot be sampled without affecting their state. Therefore, *in situ* measurements of density are necessary. The conventional density control and measurement tests such as sand cone, rubber balloon, and nuclear density meter have their limitations when sandy soils are loose or submerged. In such situations,

---

* Also accepted for presentation and publication in the proceedings of the First International Symposium on Penetration Testing (ISOPT-1), USA, 1988.

these tests would be almost impossible to perform. Penetration tests such as the standard penetration test (SPT) or cone penetration test (CPT) may be performed to estimate the *in situ* densities of soil formations.

Background

The conventional static cone penetrometer test procedure consists of progressively penetrating the soil under a static force. The 60° cone (area 10 cm^2) is pushed at a rate between approximately 1-2 cm/sec. Using a stepped procedure, the cone penetrometer tests are performed until the final depth is reached. Continuous records of the cone penetration and the casing penetration resistances are maintained. Useful correlations between cone penetrometer and other test methods such as SPT and vane shear have been presented by several authors[3-5].

Penetration tests for quality control have already been tried in different parts of the world. A sample of such utilization follows.

1. A 2-ton penetrometer was used to control compaction of runways for the Leopoldville-Kinshassa airport in Congo[6]. The values of point resistance, q_c, in the quartzitic sand ranged from 15.3-20.4 kg/cm^2 (1.5-2.0 MPa) before compaction and increased to a range of 51-76 kg/cm^2 (5-7.5 MPa) after compaction. As a result of these tests, specifications for the control of compaction were set up based on the use of the penetrometer.

The control method was found very effective for sands where water content was very uniform. The method had several advantages such as:
(a) Reduced number of samples.
(b) No disturbance to the prepared surface from sampling.
(c) Direct and rapid results.

2. The static penetrometer has been used on various occasions in France for the control of compaction of fills[6]. A quality of compaction of fills in terms of point resistance (q_c) of the static penetrometer for gravelly and sandy fills for the Rhone-Alpes area was summarized and that permitted a quick method of determining the degree of compaction of fill project in the Rhone-Alpes area. These results indicate that the penetrometer is a useful tool to control compaction and it is more economical than to run field density tests as the work progresses. Furthermore, there is always disturbance of the soil involved in performing a proctor test.

3. Webb and Hall[7] studied the effects of vibroflotation on clayey sands by means of the SPT and Dutch static penetrometer. As a results of this study, they estimated that the static cone penetrometer provides a satisfactory and economical means of checking the amount of compaction obtained by vibroflotation.

4. Mitchell[8] discussed utilization of *in situ* tests in design and evaluation of a large sand densification project for the Jebba Hydroelectric Development in Nigeria. He reported that correlations between CPT tip resistance, relative density, and depth were used successfully to assure that the required ground improvement had been achieved.

Similar studies as to the subject of this paper, were conducted by investigators in which the standard penetration test was used. Gibbs and Holtz[9] performed a laboratory research programme which established relationships between relative density and penetration resistance and also the effect of varying overburden pressures. The results of this work are widely referred to in the geotechnical literature.

In 1967, Bazaraa[10] obtained 1300 penetration values for dry cohesionless and submerged coarse cohesionless soils at 25 different sites. From these values, a full study was published which included relationships between relative density (RD), penetration resistance (N) and overburden pressure (P)[11]. He suggested that:

$$N = 20RD^2 (1 + \mathrm{P}) \text{ for } P \leqslant 0.75 \text{ kg/cm}^2 \text{ (73.6 kPa)}$$

and $N = 20RD^2 (3.25 + P) \text{ for } P \geqslant 0.75 \text{ kg/cm}^2 \text{ (73.6 kPa)}$

New[12] also presented similar relationships between standard penetration resistance and relative density of sand. As it is recognized in the documented literature, the penetration resistance is a very useful and practical method for measuring field density at shallow depths of sandy fills and for quality control of compaction of projects such as highways, dams and the densification of natural soils. In most of these laboratory and field studies for developing relationships between the commonly used density descriptions and the penetration resistance of sand, the split barrel penetration test was used. Schmertmann[13] suggested that the static cone penetration test is superior to the standard penetration test in evaluating the condition of the sand before and after compaction. This encouraged the authors to explore the relationships between densities, penetration resistance and overburden pressure of different types of sands using the static cone penetration tests.

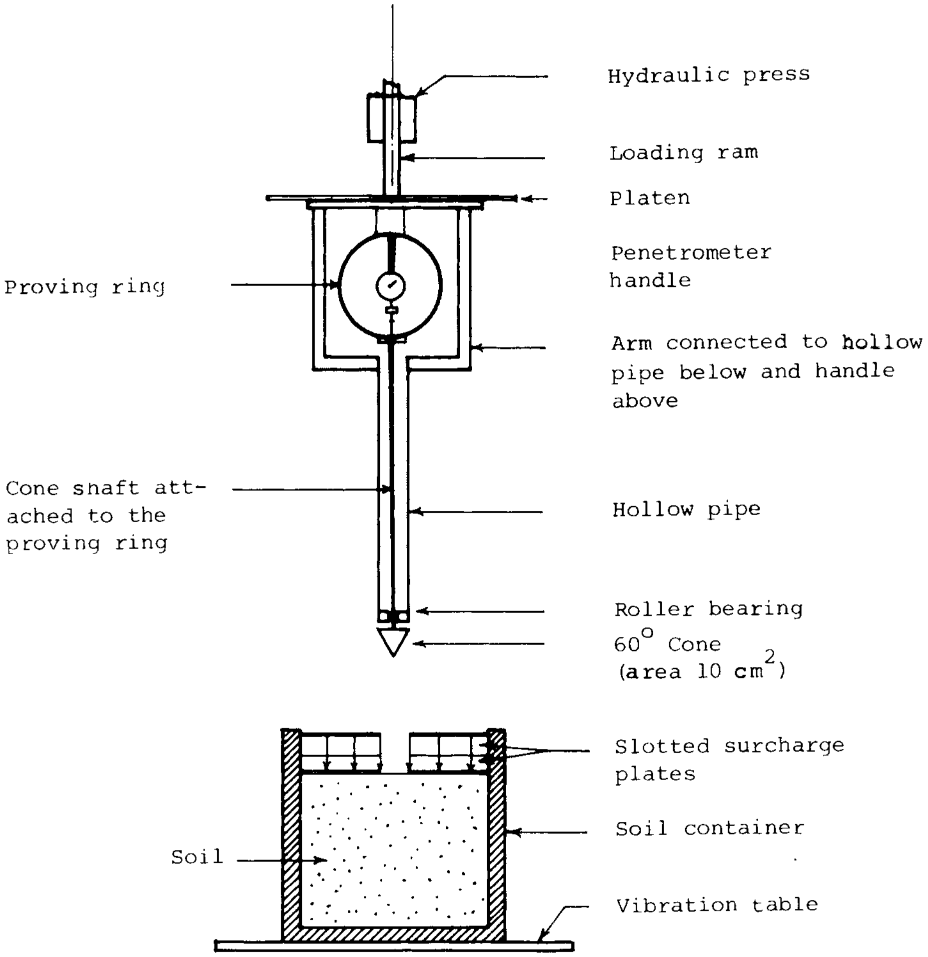
KAU Cone Penetrometer Device

The KAU penetrometer used in this study is a static cone penetrometer which is a modification of the Vicksberg penetrometer manufactured by Wykeham Farrance Inc. It consists of a 1 meter long shaft, with a handle at its upper end, different load capacities proving ring to sustain a maximum of 500 kgf (4.9 kN) complete with dial gauge, a cone of 10cm^2 base area with 60° apex angle.

A modification of this device was introduced in order to avoid frictional resistance on the shaft by adjusting a thin hollow polished stainless steel pipe around the shaft and connecting it directly to the handle, so that any frictional resistance on the hollow steel pipe surface will not be measured by the proving ring. This modified static cone penetration device (Sketch 1) is designed to measure only the point resistance at different shallow depths of fills for the purpose of density quality control.

Other Test Accessories

In addition to the cone penetrometer, the test accessories included a reinforced plexiglass tank 50cm diameter and 60cm deep which was used for penetration measurements. Also, equipments needed for running standard proctor compaction test were utilized as will be discussed later.



SKETCH 1. Schematic of KAU cone penetrometer assembly and test set-up.

In the later stages of the work, relative density test molds, a vibrating table 76 × 76cm (3600rpm) for specimen preparation, a hydraulically operated compression press for conducting penetrometer tests were utilized. In addition, a set of slotted weights was used for the application of surcharge loads on soil during testing.

Experimental Procedure

Two types of air dry granular soils (Table 1) were used in this experimental investigation in which relationships between densities, penetration resistance and surcharge loads were determined from the analysis of data collected by performing tests using the following procedure.

TABLE 1. Classification and physical properties of test sands.

Sand Designation		Ottawa Sand	Rolaco Sand
Source		Imported from Germany	Collected from a site in Jeddah, Saudi Arabia
Color		Brownish gray	Light brown
Classification:	Unified System	SP	SW
	AASHTO System	A-3(0)	A-3(0)
Co-efficient of uniformity (Cu)		1.33	6.35
Co-efficient of curvature (C_z)		0.98	0.98
Maximum grain size		1.18mm	2.0mm
Percent passing sieve # 200		0	7.75
Specific gravity (G_s)		2.64	2.64

Twenty-five samples of each granular soil were prepared for the purpose of performing the cone penetrometer tests. These samples were prepared in relative density molds and they were densified to the required density by vibration, with a certain surcharge load for a preselected duration. The densities used ranged from a loose state to a value equivalent to the dense state. Five density values were maintained and for each, five different surcharge loads were applied ranging between 0 to 14 kgf (137 N) and from which, equivalent depth of soil surcharge could be worked out corresponding to each density. These surcharge loads were left for 10 minutes prior to the performance of the static cone penetrometer test. The exact measurements for calculating the volume of the sample were done after the application of the equivalent surcharge load and directly before the cone penetration. These volumes were used in calculating the equivalent exact density corresponding to the cone penetration resistance reading. The values of penetration resistance reading were recorded at a time when the cone tip of the penetration reached the middle depth of the samples. The penetration for all samples was maintained at a rate of about 1cm per second.

Results and Discussion

The penetrometer has been modified as explained earlier to eliminate any frictional effects on the penetration readings. Thus, only the point resistance (q_c) is measured, which may be estimated from Terzaghi's formula[14]:

$$q_c = \gamma D N_q$$

The value of N_q is dependent on the angle of internal friction, ϕ, which is greatly influenced by the density of the soil. For a homogeneous soil, the angle of internal friction ϕ and N_q are theoretically uniform throughout its depth. This could support the assumption that the penetration resistance should increase linearly with depth, or in other words, with increasing surcharge. This assumption can be seen from Fig. 1 which shows the relationship between the penetration resistance and the surcharge for dry Ottawa sand tested in a tank 60cm deep and 50cm diameter, placed at a density of 1.58 g/cm^3 (15.5 kN/m^3) and in which penetration readings were taken at 10cm depth intervals. Figure 2 strongly confirms the linearity of penetration resistance with depth, in which two fillings of the same soil in the tank at the same density gave almost the same results. The minor variation in penetration readings could be due to some experimental sources of errors, such as placing of soil in the tank, otherwise the reproducibility is very good.

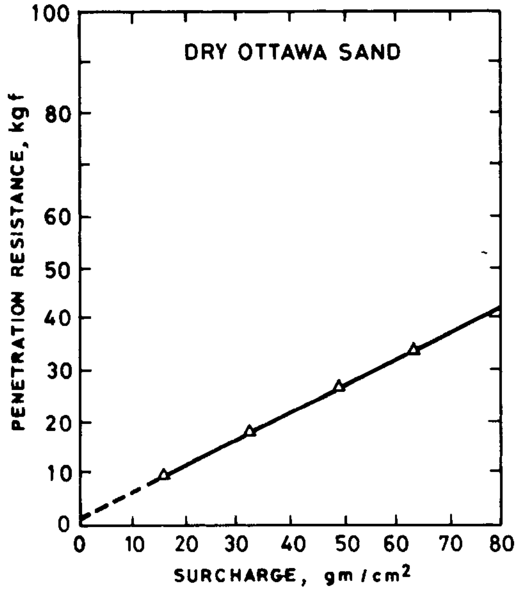


FIG. 1. Relationship between surcharge and cone penetration resistance.

Compaction tests were also conducted (ASTM D 698-70, method B) using a mould 15.24cm in diameter and 11.64cm high. The bigger mould was selected to eliminate or reduce any effects from the sides of the mould during penetration testing. After compacting the soil at a certain water content, penetration reading was taken at a

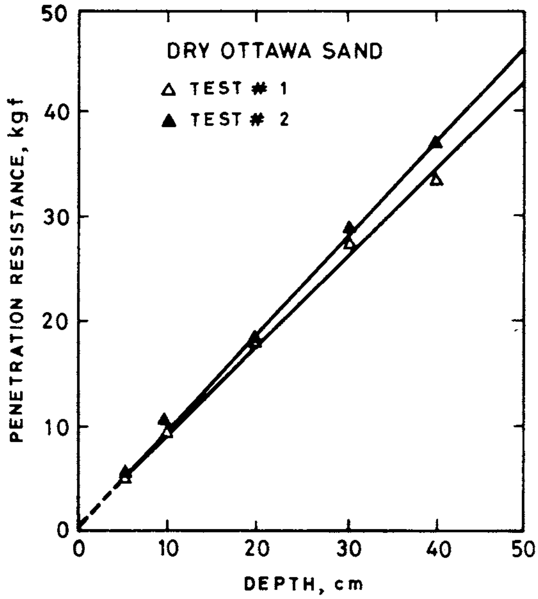


FIG. 2. Relationship between depth and cone penetration resistance.

depth of 5cm from the surface of the soil. Figure 3 represents the compaction curve and the variation of penetration resistance with water content as a result of these tests. It can be seen from this figure that the shapes of the two curves are very similar

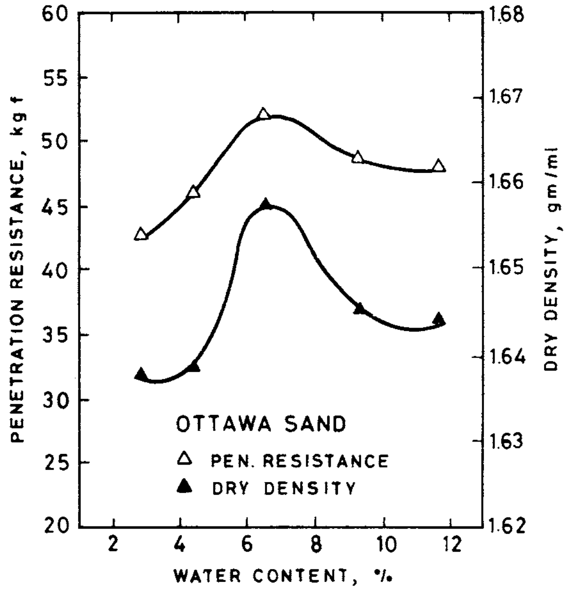


FIG. 3. Water content, dry density and cone penetration resistance relationships.

which makes the idea of predicting dry densities from penetration readings quite feasible.

Samples of air dry Ottawa sand placed at preselected densities that range from 1.55 gm/cc (15.21 kN/m^3) to 1.64 gm/cc (16.1 kN/m^3) were prepared. Surcharge weights ranging between no surcharge to 14 kgf (137N) were placed on samples on each density. Penetration readings were taken at 5cm depth of penetration. Figure 4 was plotted using linear regression polynomial to present the relationship between penetration resistance and surcharge for the different density values.

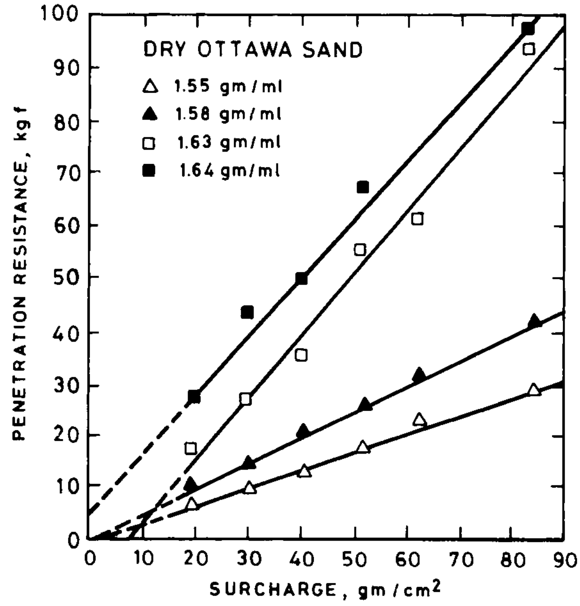


FIG. 4. Surcharge versus cone penetration resistance relationships for various dry densities.

It can be seen from this figure that for a constant value of density, the penetration resistance increases with increasing surcharge pressure. For the same surcharge pressure, penetration resistance increases with higher values of densities, as expected. Equivalent depth to soil surcharge at same densities, as in Fig. 4, are plotted in Fig. 5 keeping other variables constant. Figure 6 is actually a calibration curve obtained from Fig. 5 for density versus penetration resistance at 10,20,30,40 and 50cm penetration depths. The values of penetration resistance were calculated using the regression equations of Fig. 5, in which linear fitting was used to plot Fig. 6. A statistics analysis program (STATPACKAGE) used to check the goodness of fit and regression coefficient for each line (Table 2) generally indicated excellent fitting. Using 5% level of significance, the t-test showed that the null hypothesis was rejected for all except the first line, although the regression coefficient is high.

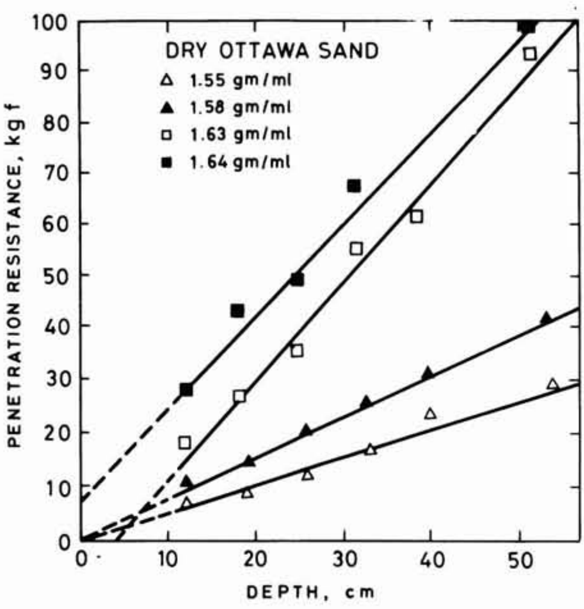


FIG. 5. Depth versus cone penetration resistance relationships for various dry densities.

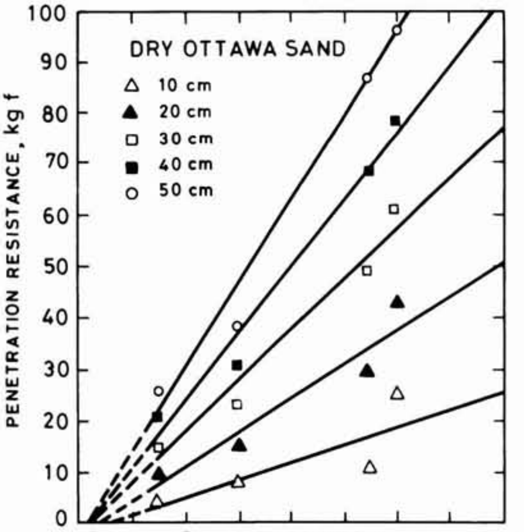


FIG. 6. Relationships between dry density and cone penetration resistance (linear regression)

TABLE 2. Statistical parameters of the calibration lines in Fig. 6, using linear fitting $y = a + bx$ (Ottawa sand).

Line	*a*	*b*	Co-variance	Variance	Goodness of fit	Regression Coefficient
10 cm line	-2.675 E02	1.750 E02	0.315	2.071 E01	0.67	0.82
20 cm line	-5.117 E02	3.354 E02	0.604	1.465 E01	0.91	0.95
30 cm line	-7.559 E02	4.958 E02	0.892	1.234 E01	0.96	0.98
40 cm line	-1.000 E03	6.564 E02	1.181	1.384 E01	0.98	0.99
50 cm line	-1.244 E03	8.166 E02	1.470	1.918 E01	0.98	0.99

The lines in Fig. 6 or the regression parameters could be used to check placement densities of Ottawa sand for 10 to 50cm penetration depths. Figure 7 shows same relationships of Fig. 6 in which second degree nonlinear fitting was used for the same data. The shapes of the curves in Fig. 7 indicate an excellent correlation, but since the linear fitting is easier and faster, it is preferred.

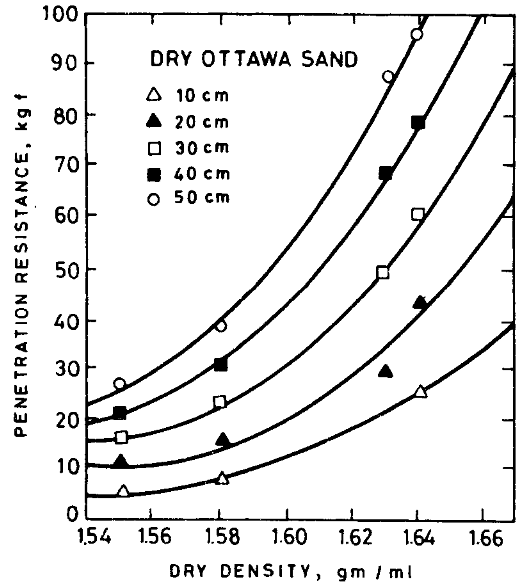


FIG. 7. Relationships between dry density and cone penetration resistance (high order regression).

The *a* and *b* parameters given in Table 2 were used to determine the densities of the soil at the levels where the penetration resistances were recorded in the tank, Fig. 2. The calculated densities coincide reasonably with the placement density 1.58 gm/cc as shown in Fig. 8.

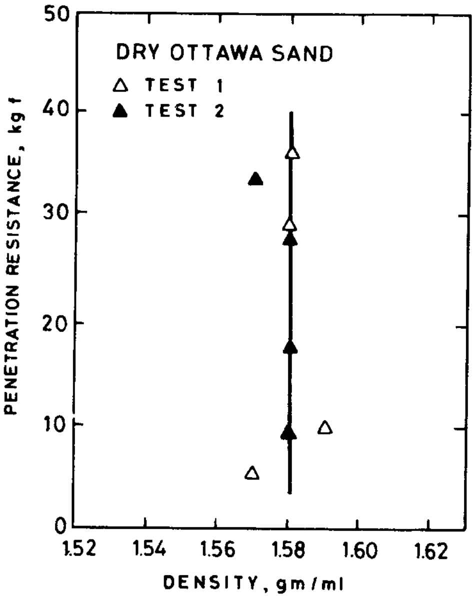


FIG. 8. Density measurements in model tank using cone penetrometer.

Samples of air dry silty sand soil (Rolaco soil) were prepared and tested following the same procedure used for the Ottawa sand above. Densities investigated for this soil ranged from 1.52 gm/cc (14.91 kN/m^3) to 1.69 gm/cc (16.58 kN/m^3). Similar finding to that of Ottawa sand case was observed. Figure 9 shows the calibration lines

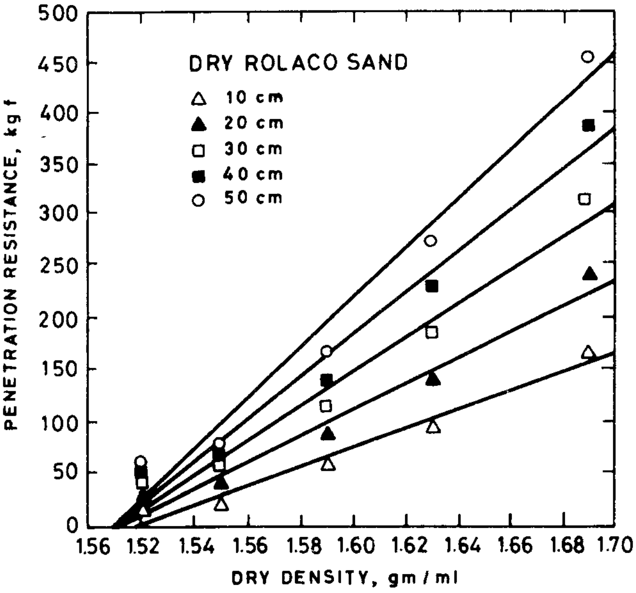


FIG. 9. Relationships between dry density and cone penetration resistance (linear regression).

(density versus penetration resistance) obtained for 10,20,30,40 and 50cm penetration depths.

In Table 3, statistical parameters of the Rolaco soil data are presented. Using 5% level of significance and the t-test showed that the null hypothesis was rejected for all lines. Fig. 10 also indicated an excellent correlation in the shapes of the different curves by using second degree nonlinear fitting approach.

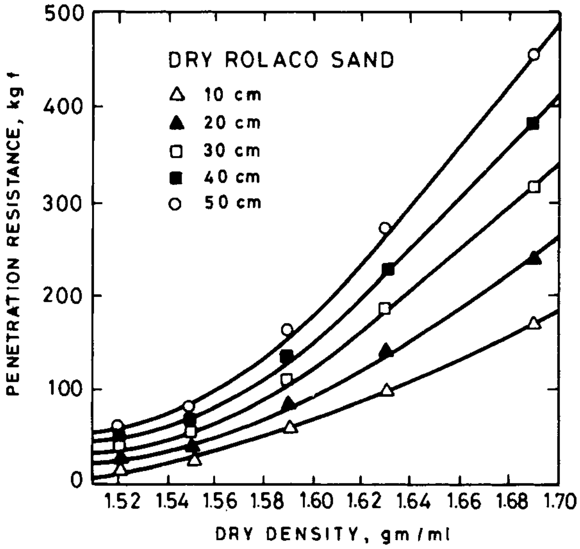


FIG. 10. Relationships between dry density and cone penetration resistance (high order regression).

TABLE 3. Statistical parameters of the calibration lines in Fig. 9, using linear fitting $y = a + bx$ (Rolaco sand).

Line	*a*	*b*	Co-variance	Variance	Goodness of fit	Regression Coefficient
10 cm line	-1.442 E02	9.486 E02	4.250	9.246 E02	0.97	0.986
20 cm line	-1.991 E03	1.314 E03	5.885	1.750 E02	0.97	0.986
30 cm line	-2.541 E03	1.679 E03	7.523	2.857 E02	0.97	0.986
40 cm line	-3.091 E03	2.045 E03	9.161	4.236 E02	0.97	0.986
50 cm line	-3.641 E03	2.411 E03	10.780	5.888 E02	0.97	0.986

The above discussion and analysis indicate that calibration lines of each soil type are different and the static cone penetration methods can be used as a quality control procedure for checking densities in the field of soil layers with shallow depths and in the laboratory. The following procedure is proposed:

1. Determine the depth of penetration in the soil to be checked. It could be to the middle of soil layer.

2. Prepare samples of the same soil placed in moulds at a range of densities, that include the density expected.
3. Put a surcharge load on the samples, equivalent to the overburden at the depth of recording the penetration resistance.
4. Plot the points of density-penetration resistance and use linear regression to fit a line through these points. This line is the calibration line.
5. Penetration resistance is measured in the field at several points and from the calibration curve corresponding densities are determined.

Conclusion

In the light of this study the following conclusions may be drawn:

1. Provision of sleeve pipe around penetration rod greatly helped in accurate measurement of cone resistance (q_c) alone.
2. Static cone penetrometer is found to be a convenient, reliable and accurate tool for evaluation of density of granular soils free from gravel in the laboratory or perhaps in the field as well.
3. The cone resistance is found to vary linearly with depth or surcharge for the same relative density of a homogeneous (sandy) soil strata.
4. A procedure is outlined for measuring laboratory or *in situ* density using a cone penetrometer device.
5. The variation of cone resistance for the sandy soils investigated is found to follow very closely the pattern of compaction curve.

References

[1] **Graaf, H.C. Van de** and **Zuidberg, H.M.**, Field Investigation, *in: The Netherlands Commemorative Volume,* pp. 29-44 (1985).

[2] **Verruijt, A., Beringen, F.L.** and **Leeuw, E.H. de,** (eds), *Proc. Second European Symposium on Penetration Testing ESOPT 2, Amsterdam, The Netherland* (1982).

[3] **Meyerhof, G.G.,** Shallow Foundations, *J. Soil Mech. Found. Div., ASCE,* **91**(SM2): 21-31 (1965).

[4] **Schmertmann, J.H.,** Static Cone to Compute Static Settlement Over Sand, *Proceedings ASCE,* **96**(SM3): 1011-1043 (1970).

[5] **Larriere, A.,** Measurements Results Correlations, *Foundation Engineering, in:* **Pilot, G. (ed.),** *Soil Properties, Foundation Design and Construction,* vol. **1,** Presses de l'ecole National Ponts et Chausses, Paris, pp. 115-182 (1982).

[6] **Sanglerat, G.,** *The Penetrometer and Soil Exploration,* Elsevier, Amsterdam (1972).

[7] **Webb, D.L.** and **Hall, R.I.,** Effect of Vibroflotation on Clayey Sands, *Proc. Am. So. Civ. Engr.-J.S. M.F. Div.* 6882(6): 1365-1376 (1969).

[8] **Mitchell, J.K.,** "Ground Improvement Evaluation by *In Situ* Tests", Use of *In Situ* Tests in Geotechnical Engineering, *Geotechnical Special Publication No. 6, ASCE,* pp. 221-236 (1986).

[9] **Gibbs, H.J.** and **Holtz, W.G.,** Research on Determining the Density of Sands by Spoon Penetration Testing, *Proc. 4th Intern. Conf. Soil Mechs. and Found. Eng., London,* Vol. **1,** pp. 35-39 (1957).

[10] **Bazaraa, A .R.,** *Use of the S.P.T. for Estimating Settlements of Shallow Foundations on Sand.* Ph.D. Thesis, Univ. of Illinois, Urbana, Ill., 381 p. (1967).

[11] **Bazaraa, A.R.,** Standard Penetration Test, *in:* **Pilot, G. (ed.)** *Foundation Engineering,* Vol. **I,** Presses l'ecole National des Ponts et Chausses, Paris, pp. 65-72 (1982).

[12] **New, B.M.,** A Note on the Relationships between Penetration Resistance and Density of Sand, *Ground Engineering,* pp. 43-45 (1978).

[13] **Schmertmann, J.H.,** "Sand Densification by Heavy Vibratory Compactor", Disc. Proc. Paper 6656, *JSMFD ASCE* 96(SM1): pp. 363-365 (1970).

[14] **Terzaghi, K.** and **Peck, R.B.,** *Soil Mechanics in Engineering Practice,* John Wiley and Sons Inc., 566 p. (1967)

تقدير الكثافة باستخدام مقياس اختراقية المخروط الإستاتي

زكي عبد الله بغدادي ، فؤاد محمد غزالي و أحمد مختار خان
قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك عبد العزيز
جدة ، المملكة العربية السعودية

تعرض هذه الورقة نتائج بحث عن استخدام مقياس اختراقية المخروط الإستاتي للتنبؤ بكثافتي تربتين رمليتين مجففتين بالهواء . قيست قيم مقاومة الاختراق للمخروط (q_c) لعينات تربة جُهِّزت بكثافات محددة مع وضع أحمال إضافية مختلفة . استعملت طرق الانحسار الخطي لإيجاد علاقات بين قيم (q_c) والأحمال الإضافية وأعماق الاختراق . وبناء على نتائج الاختبارات أُعطيت منحنيات قياس للتنبؤ بكثافات التربة . كذلك لُخصت طريقة تحديد كثافات التربة باستخدام مقياس اختراقية المخروط .