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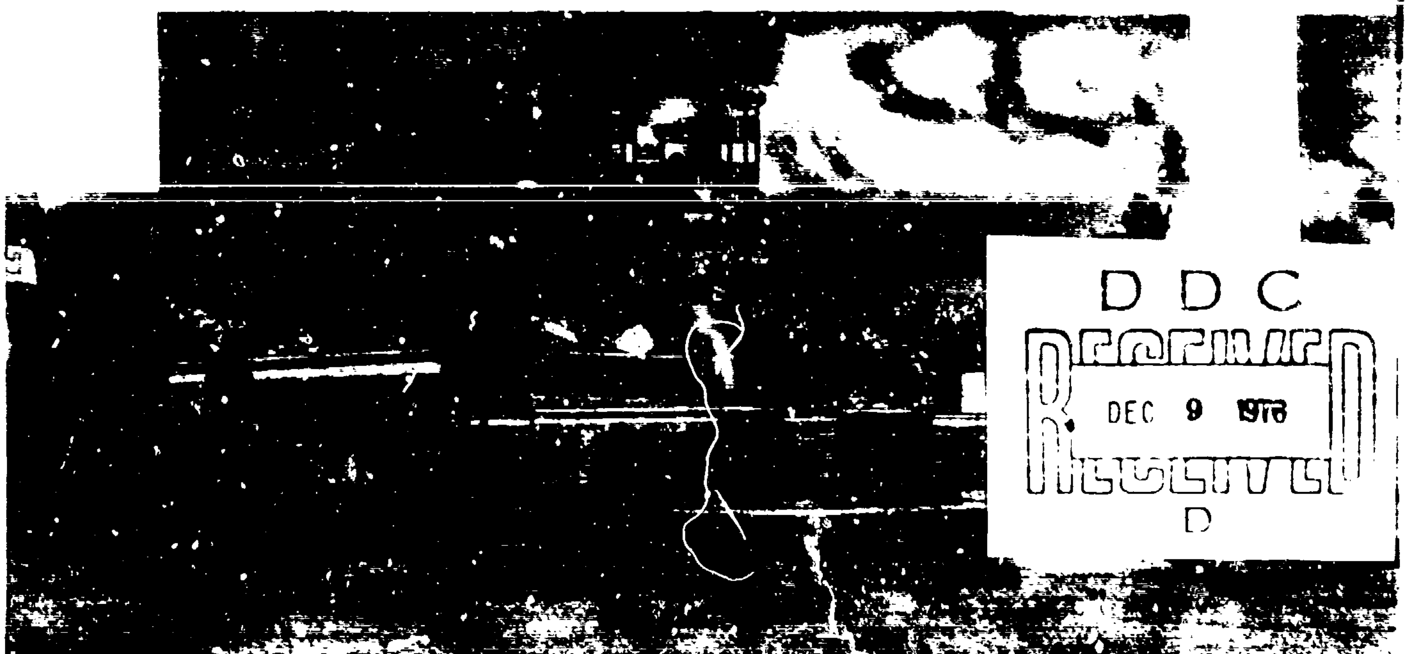
STANDARD PENETRATION TEST AND RELATIVE DENSITY

by

K.-J. Melzer



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13. ABSTRACT

Since ground water greatly influences penetration resistance of soil, an empirical relation was established between the number of blows applied in the standard penetration test to sand below ground-water level and the corresponding number applied to air-dry sand at the same relative density. Also, since the number of blows was found to depend not only on the relative density but also on the compactibility and the grain size of the penetrated sand, an empirical relation was developed between the number of blows and the relative density, with compactibility and mean grain diameter taken into account. This relation was verified by results from laboratory tests conducted with a small static penetrometer.

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FOREWORD

This paper was prepared by Dr. K.-J. Melzer as one of the United States's contributions to the Fourth Pan American Conference on Soil Mechanics and Foundation Engineering in San Juan, Puerto Rico, 14-18 June 1971. The conference was organized as a Regional Conference of the International Society of Soil Mechanics and Foundation Engineering and as a Specialty Conference of the American Society of Civil Engineers.

The research reported upon herein was based on the author's doctoral dissertation and data collected in studies conducted at the U. S. Army Engineer Waterways Experiment Station (WES) under DA Project 1T062103A046, "Trafficability and Mobility Research," Task 03, "Mobility Fundamentals and Model Studies," under the sponsorship and guidance of the Research, Development and Engineering Directorate, U. S. Army Materiel Command.

COL Ernest D. Peixotto, CE, was Director of the WES during this study and preparation of this paper. Mr. F. R. Brown was Technical Director.

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STANDARD PENETRATION TEST AND RELATIVE DENSITY

La Prueba Normal de Penetración y la Densidad Relativa

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SYNOPSIS

Since ground water greatly influences penetration resistance of soil, an empirical relation was established between the number of blows applied in the standard penetration test to sand below ground-water level and the corresponding number applied to air-dry sand at the same relative density. Also, since the number of blows was found to depend not only on the relative density but also on the compactibility and the grain size of the penetrated sand, an empirical relation was developed between the number of blows and the relative density, with compactibility and mean grain diameter taken into account. This relation was verified by results from laboratory tests conducted with a small static penetrometer.

SINOPSIS

Debido a que el agua subterránea grandemente influye la resistencia a la penetración de un suelo, se estableció una relación empírica entre el número de golpes en la prueba normal de penetración (Standard Penetration Test) de una arena bajo el nivel freático y el correspondiente número en una arena seca (i.e. sobre el nivel freático) con la misma densidad relativa. Asimismo, porque se encontró que el número de golpes depende no solo de la densidad relativa sino también de la compacticidad y el tamaño del grano de la arena penetrada, se desarrolló una relación empírica entre el número de golpes y la densidad relativa, tomando en cuenta la compacticidad y el diámetro medio granular. Esta relación se verificó con los resultados obtenidos en ensayos de laboratorio ejecutados con un penetrómetro estático pequeño.

INTRODUCTION

One of the main problems encountered in subsoil exploration is in situ determination of relative density and related characteristics of cohesionless soils. The deep penetration test, one of the earliest approaches to solution of this problem, yields results that are used to empirically correlate certain soil properties with resistance measurements. In use today are not only a variety of static and dynamic penetrometers, but also numerous empirical and theoretical relations between the results from specific penetration techniques and the properties of cohesionless soils, e.g. results from the standard penetration test and relative density.

The standard penetration test (SPT) was developed primarily for sampling cohesive soils. Its secondary purpose was to measure penetration resistance by counting the number of blows required to drive a sampler 1 ft into the soil. The test also is used today in cohesionless soils, but primarily as a method for measuring penetration resistance rather than for obtaining undisturbed samples.

The author is aware that there is a controversy concerning the applicability of the standard penetration test (Moretto, 1963; Ireland et al., 1970). Nevertheless, a technique will be shown in this paper for evaluating the relative density of sand from the number of blows obtained from the standard penetration test by taking into account the compactibility and the grain size of the sand under consideration and the possible existence of ground water. Furthermore, the technique will be shown to be applicable to the evaluation of relative density from penetration resistance measurements with static cone penetrometers. The concept, based on a few general considerations of what happens during a cone penetration into sand, is purely empirical, and it is offered only as a beginning and an encouragement for further research.

TESTS

Results of standard penetration tests conducted under laboratory conditions in four sands with different gradations (sands 1-4 in table I)

Table I. Sand Properties and Types of Test

Sand No.	Source of Data	Type of Penetrometer	Moisture Condition	Compactibility D' *	Coefficient of Uniformity C_u	Mean Grain Diameter d_m **
						mm
1	U. S. Bureau of Reclamation (1953); Gibbs and Holtz (1957)	SPT	Air-dry	2.36	10.0	0.23
2	U. S. Bureau of Reclamation (1953); Gibbs and Holtz (1957)	SPT	Air-dry, submerged	1.31	5.0	1.40
3	Menzenbach (1959)	SPT	Air-dry	0.62	2.0	0.42
4	Schultze and Melzer (1965)	SPT	Air-dry, damp, submerged	0.76	2.4	0.55
5	Melzer (1971)	Cone	Air-dry	0.51	1.5	0.12
6	Melzer (1971)	Cone	Air-dry	0.59	1.5	0.27
7	Melzer (1971)	Cone	Air-dry	0.63	2.5	0.50

* Compactibility $D' = (e_{max} - e_{min})/e_{min}$ according to Terzaghi (1925).

** As defined by Burmister (1938).

were used to develop the concept discussed herein. Its applicability to the determination of relative density from static penetration resistance was evaluated from cone penetrometer tests conducted recently at the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, in three different sands (sands 5-7 in table I), also under carefully controlled laboratory conditions. The WES tests were conducted with a mechanical cone penetrometer; the cone has a base diameter of 2 cm and an apex angle of 30 degrees. This penetrometer was not developed for deep penetrations, but for exploration of the top layer (0 to 15 cm) of the soil under consideration. The penetration speed in these tests was 0.03 m/s.

A detailed description of the various soils and test procedures is not within the scope of this paper; therefore, only certain pertinent properties of the seven sands are listed in table I, together with the sources of data and the penetrometers used. Grain-size distribution curves are presented in fig. 1.

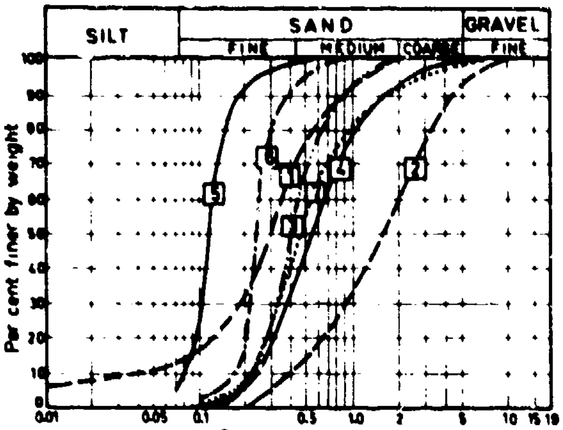

Fig. 1 Grain-Size Distribution Curves of Sands Investigated

INFLUENCE OF GROUND WATER

In a permeable sand with a given relative density D_r, the number of blows N of the standard penetration test is smaller below ground-water level than above the ground water (Menzenbach, 1959; Rodin, 1961; and Gawad, 1964). Some investigations seem to indicate that the magnitude of this difference depends on N and, therefore, on D_r, which is directly related to N. But because most results were based on field tests in which relative density could seldom be measured accurately, there is some doubt as to whether the relative density above the ground-water level was, in fact, the same as that below.

To examine the effect of ground water more closely, the results of the laboratory tests on sand 4 (table I), which was tested not only in air-dry and damp states but also submerged, were evaluated as follows: The number of blows N counted in tests conducted at a certain depth and at a certain relative density with no ground water present was compared with the number of blows N' from tests conducted below ground water at the same depth and the same relative density. A statistical analysis of the data yielded a linear relation between N and N' (fig. 2) for this sand. In fact, this relation shows that for low N values the decrease (in percentage of N) from N to N' is larger than for high N values, and the difference, therefore, depends on relative density. A similar evaluation of the results of tests on sand 2, the only other sand without silt particles for which results from tests in air-dry and submerged states were available, shows the data points clustering fairly well around the relation between N and N' for sand 4. From these results, a cautious conclusion might be drawn that for medium and coarse sands, the relation between N and N' is more or less independent of sand type.

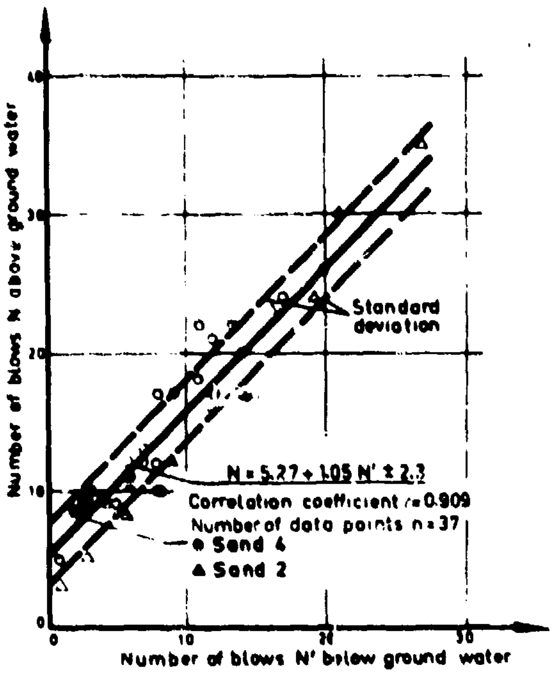

Fig. 2 Influence of Ground Water on the Number of Blows in the Standard Penetration Test

The number of blows is smaller below ground water than above because the effective unit weight of the sand in a submerged state is smaller than in a dry or wet state and because the dynamic action of the penetrating sampler causes a quicksand effect, at least in very loose to medium-dense sands, resulting in decreased penetration resistance. Therefore, the number of blows measured below the ground-water level in medium and coarse sands should be corrected for these influences by means of the relation in fig. 2 before an estimate of relative density is made.

RELATIVE DENSITY EVALUATED FROM NUMBER OF BLOWS

In recent years, comparison of relative density values evaluated from the number of blows by various existing relations sometimes led to contrasting results (Doscher, 1967; Tavenas et al., 1970), possibly because nearly all such relations were developed from results of tests conducted in different types of sands. These deviations are not too surprising; however, the influence of the sand type on the number of blows can be taken into account by relatively simple means.

When a cone or a standard penetration test sampler penetrates a cohesionless soil, the grains are displaced. The forces required for displacement depend not only on the relative density but also on compactibility in that the grains in a highly compactible soil can be displaced with less difficulty than in a soil with a low compactibility but the same relative density. Thus, penetration resistance is greater for the latter case. Earlier investigations with penetrometers support this reasoning (Kolbuszewski, 1957; Muhs, 1969). On the other hand, penetration resistance is greater in a soil with large-diameter grains than in a soil with smaller grains. For example, when a gravel and a sand with the same relative density and compactibility are penetrated, penetration resistance is greater in the gravel. Thus, compactibility and grain size, the latter characterized by the mean diameter, influence the relation between relative density and the number of blows when the standard penetration test is used.

The general form of one proposed relation (Schultze and Melzer, 1965) for the determination of relative density from the number of blows, with overburden taken into consideration, is:

$$D_r = a_1 \log N - a_2 \gamma D + a_3 \qquad (1)$$

where D_r = relative density in percent; N = number of blows per 30 cm of penetration; γ = unit weight of the overlying soil; D = depth of the point of the penetration test below the soil surface; γD = effective overburden pressure in kg/cm^2; and a_1, a_2, and a_3 are constants. For easier interpretation and comparison, it is assumed that the tests were conducted at the soil surface, which leads to $\gamma D = 0$, and equation 1 becomes

$$D_r = a_1 \log N + a_3 \qquad (2)$$

If two sands are assumed to have different compactibilities and $a_3 = 0$, the relation between relative density and number of blows can be plotted as shown in fig. 3a.

At the same relative density, the number of blows increases with decreasing compactibility. Angle β, whose tangent corresponds to constant a_1 in equation 2, can then be seen to increase with increasing compactibility. On the other hand, if two sands are assumed to have the same compactibility (β = constant) and the same relative density, the number of blows increases with the mean grain diameter (fig. 3b). Thus, the intersection on the relative density axis, which is equivalent to constant a_3 in equation 2, decreases with increasing mean diameter.

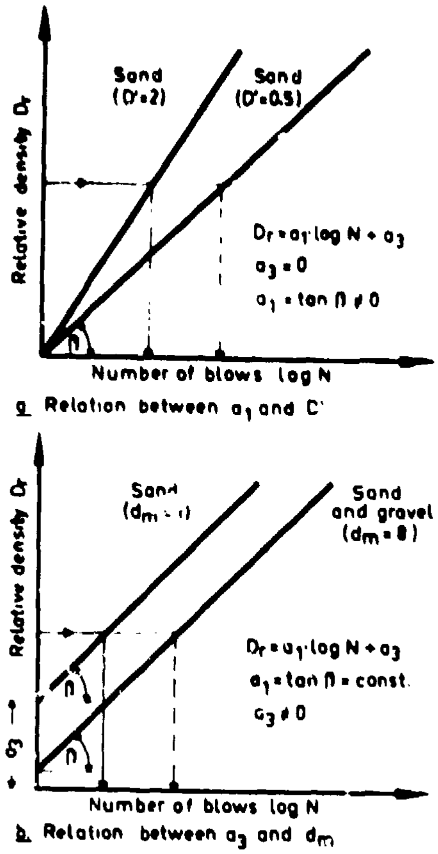

Fig. 3 Influence of Compactibility and Grain Diameter on Number of Blows

The above considerations were validated by using the results of tests with sands 1, 2, 3, and 4. If equation 2 in its general form is valid for all sands (this point is not under discussion in this paper), corresponding equations for sands 1, 2, and 3 can be established. Constants a_1 and a_3 for the relation between relative density and number of blows measured above ground water are given in table II.

Table II. Constants a_1 and a_3 (Equation 2) and a_4 and a_5 (Equation 3)

Sand No.	a_1	a_3	Penetrometer	Sand No.	a_4	a_5	Penetrometer
1	46.1	31.1	SPT	5	71.2	53.9	Cone
2	38.3	38.2	SPT	6	75.5	45.0	Cone
3	30.6	42.5	SPT	7	77.2	35.2	Cone
4	31.7	39.2	SPT				

Plots of compactibility D' versus constant a_1 (fig. 4a) and mean grain diameter d_m versus constant a_3 (fig. 4b) show agreement with the general considerations concerning the influence of D' and

d_m shown in fig. 3. As happens often, there is one point (sand 1, fig. 4b) that diminishes the validation. However, if the fact is taken into account that the data came from three sources and, therefore, may contain some scatter, it is surprising that only one point is an outlier. Thus, at least the general trend of the observations concerning the influence of compactibility and grain size seems to be reasonable.

RELATIVE DENSITY EVALUATED FROM CONE PENETRATION RESISTANCE

To confirm the above trend and check whether the general concept is applicable to the relation between relative density and resistance to penetration of static cone penetrometers, the results of tests with sands 5, 6, and 7 were analysed as described above. A statistical analysis showed that the relation between relative density and average (0- to 15-cm depth) cone penetration resistance q_c for a specific sand can be described best by a function of the general form:

$$D_r = a_4 \log q_c + a_5 \qquad (3)$$

Constants a_4 and a_5 for sands 5, 6, and 7 are listed in table II. Plots of compactibility D' versus constant a_4 (fig. 5a) and mean

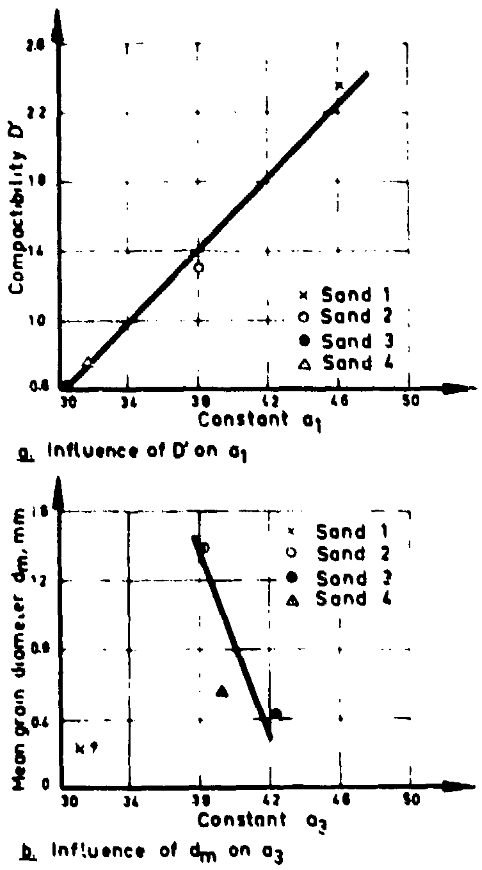

Fig. 4 Factors Affecting Relation Between Relative Density and Number of Blows

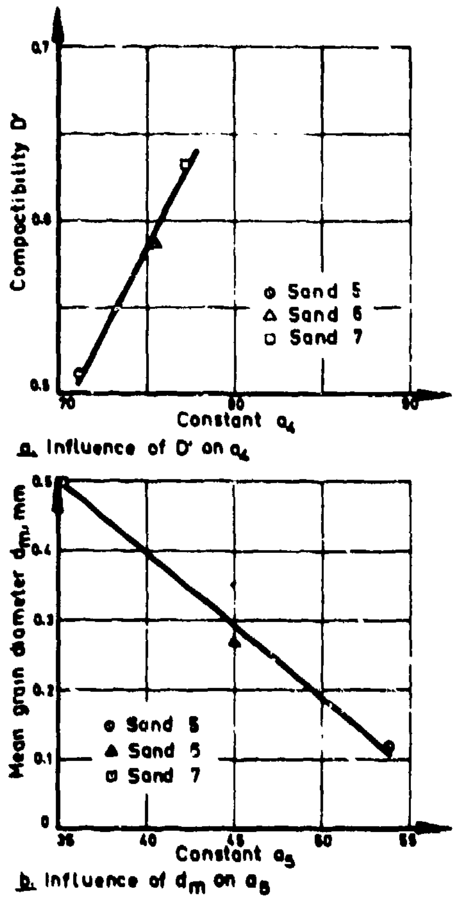

Fig. 5 Factors Affecting Relation Between Relative Density and Penetration Resistance

grain diameter d_m versus constant a_5 (fig. 5b) show the same trend observed in the results with sands 1-4, even though the overall variation of D' and d_m was not as broad in the cone penetration tests as in the standard penetration tests; soil selection was limited in the cone tests by the capacity of the pressure measuring device. Furthermore, the cone penetrometer, because of its greater sensitivity, responded much more to a change in the mean grain diameter than did the penetrometer in the standard penetration test.

CONCLUSIONS

In the standard penetration test, the number of blows measured for a given relative density is larger when the test is conducted above the ground-water level than when it is conducted in submerged sand, at least in medium and coarse sands. Thus, before any estimate of relative density can be made, the number of blows counted below the ground-water level must be corrected for this influence. The correction can be made by means of the empirically established relation in fig. 2.

The number of blows depends not only on the relative density, but also on the compactibility and the mean grain diameter of the considered sand (fig. 3). Based on a qualitative explanation, an empirical relation can be used quantitatively to take into account the effect of compactibility and mean grain diameter on the constants of a given relation between relative density and number of blows (fig. 4). Compactibility and mean grain diameter can be determined from disturbed samples taken from the borehole in which the standard penetration test is conducted.

The cone penetration resistance in the static penetrometer tests was influenced by compactibility and mean grain diameter of the investigated sands in qualitatively the same way as the number of blows was influenced (fig. 5).

Further research should be conducted to confirm and extend the basic empirical concept developed. A real standardization of the "standard" penetration test would be useful so that evaluations based on the results from various research agencies would be more valid.

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