Interpretation of Static Penetration Tests in Sand

L'Interprétation de l'Essai de Pénetration Statique

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SYNOPSIS A series of friction-cone penetrometer tests has been carried out on a dry sand in a large scale laboratory test chamber. Normally and overconsolidated stress states were used, and the factors influencing cone and sleeve resistance studied. The Friction Ratio proved to be an insensitive parameter for soil property prediction, but it was possible to correlate compressibility with cone resistance, provided the state of consolidation was known. The angle of shearing resistance could be predicted accurately for normally consolidated specimens.

INTRODUCTION

Results are presented from a series of friction cone penetrometer tests in sand under laboratory controlled stress conditions. Readings of cone resistance and friction sleeve resistance were taken for samples at three initial densities subjected to a range of K_o stress states and degrees of overconsolidation.

EXPERIMENTAL PROGRAMME

The sand was tested in the chamber shown diagrammatically in Fig. 1 and described in detail by Chapman (1974). Samples 1.2m dia. by 1.8 m in height, could be consolidated automatically under K_o stress conditions to a maximum vertical stress of 600 kPa. Readings of sample vertical compression, vertical and lateral stresses, and cone penetration, point load and friction sleeve load were automatically logged and processed to produce plots of the type shown in Fig. 2. The sand was Frankston Sand, a rounded to sub-angular medium to fine grained quartz sand with D_{50} = 0.31 mm and C_u = 2.05. Test series A, B and C were carried out at mean relative densities of 63, 88 and 98% respectively.

The penetrometer was similar to the Fugro type (De Ruiter (1971)), with a 60° apex angle, 1000 mm^2 projected area and 15,000 mm^2 friction sleeve area immediately behind the cone. The load cells were specially designed to measure cone resistance, q_c, and sleeve resistance, f_s, with a resolution of 5N, or 1% of the lowest expected load, so that friction ratio, R_f, could be determined accurately.

FACTORS INFLUENCING FRICTION RATIO

The relationships between initial density, overconsolidation ratio, lateral stress, K_o and friction ratio, R_f, were studied to investigate the value of R_f as a predictor of soil properties.

Figure 3 shows that friction ratio is essentially independent of lateral stress for a given initial density and normal consolidation,

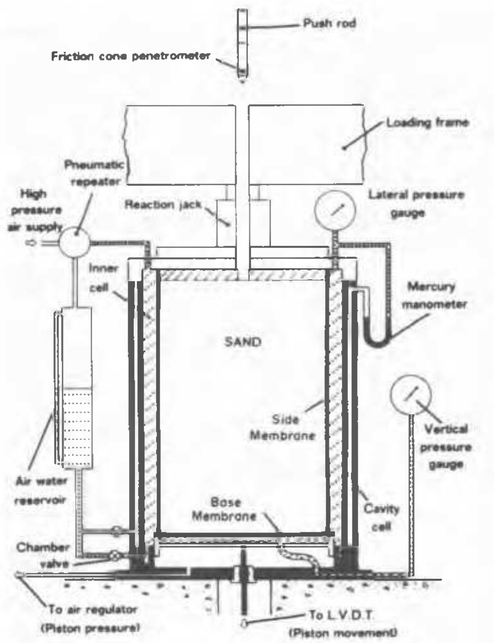

Fig. 1 Penetrometer Calibration Chamber.

and that it correlates with sample density. As shown in Fig. 4, however, this correlation is extremely insensitive for D_R below 90%. A similar correlation naturally exists between R_f and K_o. Test results for overconsolidated samples are also plotted in Fig. 4 and a more reasonable linear correlation is seen to exist. Predictions of γ_d from R_f would then require a knowledge of the state of consolidation, which is not readily determined.

For overconsolidated samples R_f correlates linearly with lateral stress, Fig. 5, and for overconsolidation ratios of two or greater the relationship appears unique. A relationship between R_f and K_o was not apparent for overconsolidated samples.

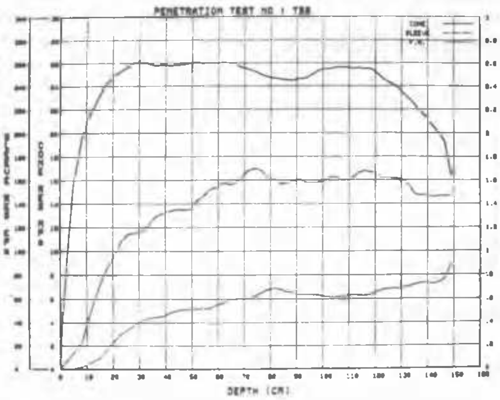

Fig. 2 Typical Test Result.

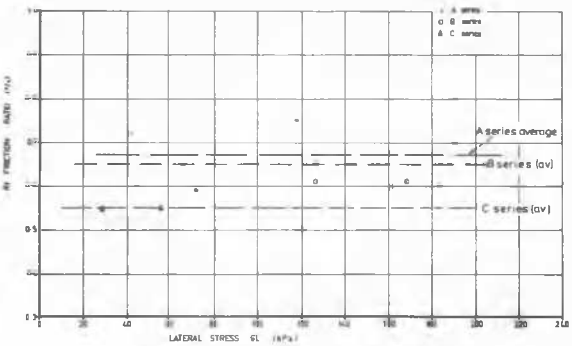

Fig. 3 Friction Ratio for N.C. Sand.

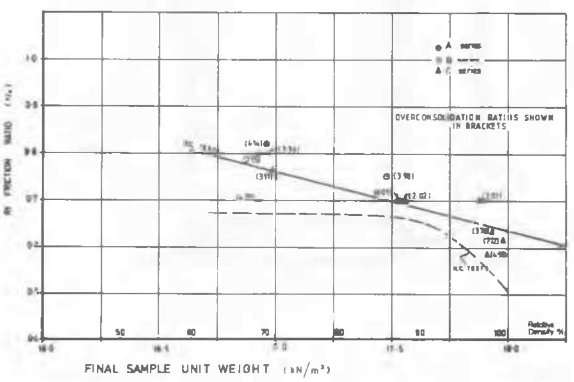

Fig. 4 Friction Ratio vs. Unit Weight.

Several workers, e.g. Begemann (1965) have concluded that friction ratio is essentially constant for a given soil type, reflecting only the average particle size. The present work has indicated trends in the variation of R_f with stress level and density, but the scatter is large, particularly for low density specimens, and R_f cannot be used by itself to predict mechanical properties of a sand deposit.

PENETRATION RESISTANCE

Cone resistance, q_c, is plotted against vertical effective stress in Figure 6 and initial relative density, D_R, after consolidation in

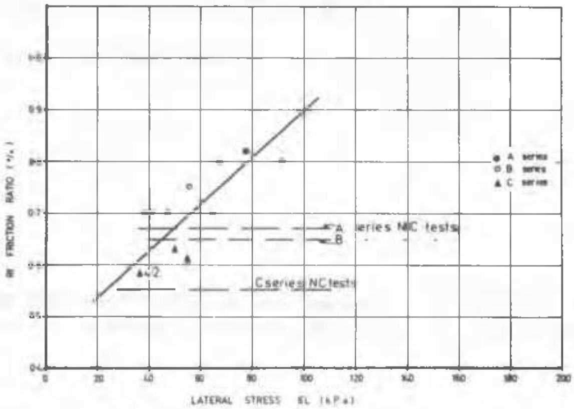

Fig. 5 Friction Ratio - O.C. Sand.

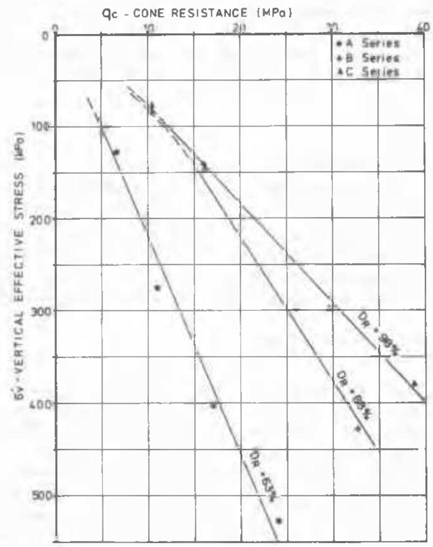

Fig. 6 Cone Resistance vs σ_v' - N.C. Sand.

Figure 7. The present study was concentrated on the vertical stress range from 75 MPa upwards, and here a near-linear relationship exists between q_c and either σ_v' or σ_H'.

The dashed lines on Figure 7 show the variation in q_c with D_R for various levels of constant vertical stress, σ_v'. Regression analysis of the data yielded the following relationship between q_c, σ_v' and γ (after consolidation):

$$\left(\frac{q_c}{p_a}\right) = 43 + \left(\frac{\sigma_v'}{p_a}\right) \left[481 \frac{\gamma}{\gamma_w} - 797\right] \qquad (1)$$

where p_a = reference pressure (atmospheric)
γ_w = reference unit weight (water).

The overconsolidated specimens naturally had higher values of lateral stress, σ_H', than normally consolidated specimens at the same level of vertical stress. This was reflected in higher values of q_c, as shown in Figure 8, at least for the A series of low density specimens. For Series B and C there were negligible changes in density during the overconsolidating process and no apparent changes in q_c with degree of overconsolidation.

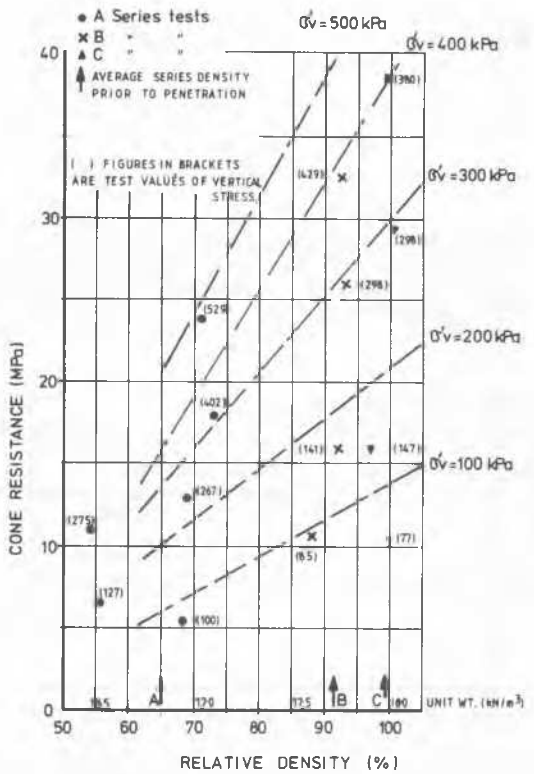

Fig. 7 Cone Resistance vs. D_R.

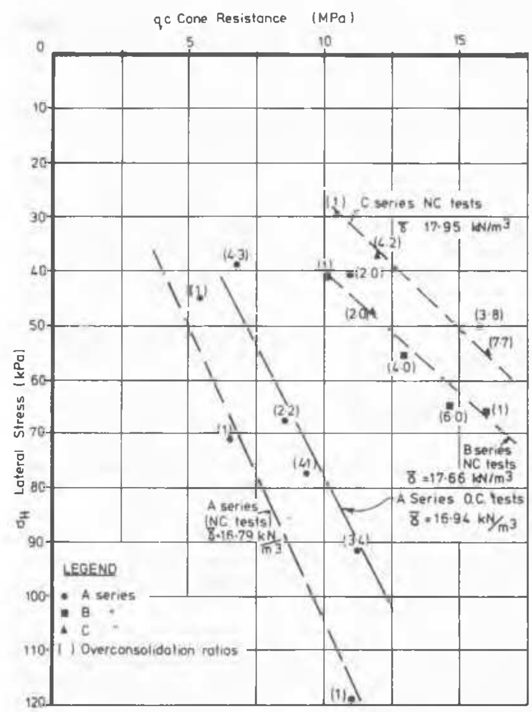

Fig. 8 Cone resistance vs. σ'_H

The data is fitted by the equation

$$\left(\frac{q_c}{p_a}\right) = 54 + \left(\frac{\sigma'_H}{p_a}\right)\left[1108\left(\frac{\gamma}{\gamma_w}\right) - 1840\right] \quad (2)$$

In theory, equation (2) could be used to determine lateral stress in a uniform deposit of this sand, but it is very sensitive to the value of γ which is not normally known with great accuracy.

MODULUS OF ONE-DIMENSIONAL COMPRESSIBILITY

Values of initial modulus, M_o, for normally consolidated specimens are plotted against cone resistance, q_c, in Figure 9. The results all lie within a narrow band and the commonly accepted expression $M_o = 3q_c$ provides a lower bound. Most of the points fall in the range M_o = 3 to 4 q_c.

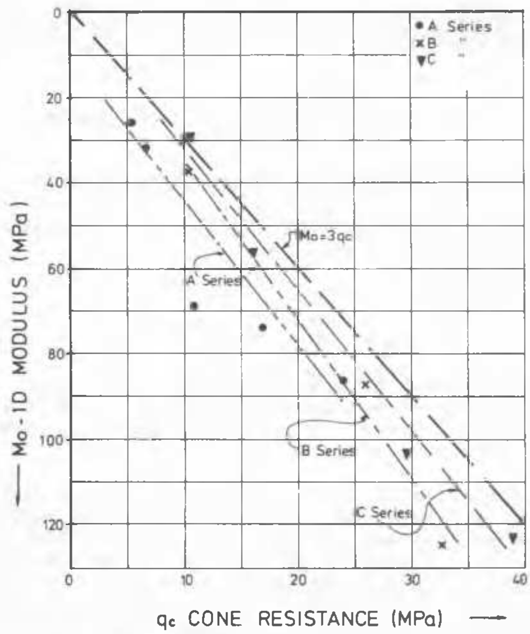

Fig. 9 Compression Modulus vs. q_c.

The picture is less clear for the overconsolidated samples, plotted in Figure 10. M_o for these tests was calculated for a small incremental reload, after unloading from maximum σ'_v to give the desired overconsolidation ratio. The points lie mainly between the lines $M_o = 8\ q_c$ and $M_o = 15\ q_c$ with a working average given by $M_o = 12\ q_c$. Most of the change occurred for overconsolidation ratios between 1 and 2. The test data was analysed for a means of predicting degree of overconsolidation from cone resistance and friction ratio, but this proved impossible unless the soil density, γ, were already accurately known. The prediction of compressibility from penetration tests is seen to require a knowledge of the state of consolidation, and it is therefore not surprising that many gross overestimates of settlement have been reported in the literature, most existing correlations being valid only for normally consolidated deposits.

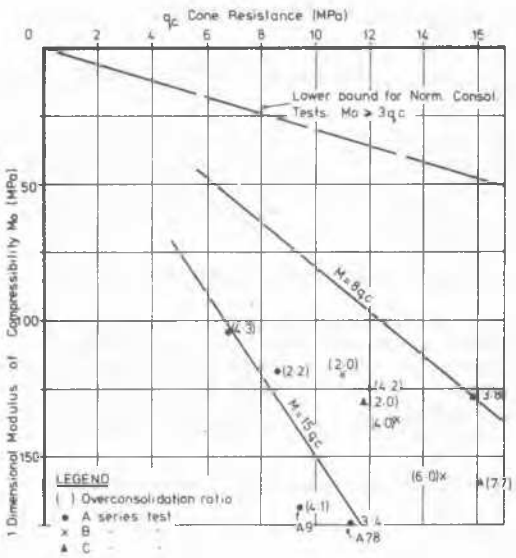

Fig. 10 Compression Modulus - O.C. Sands.

ESTIMATION OF ANGLE OF SHEARING RESISTANCE

For each test an equivalent bearing capacity factor, N_q, was calculated from

$$N_q = \frac{q_c}{\sigma'_v} \tag{3}$$

A relationship between ϕ and initial γ was established from triaxial tests on 75 mm dia. specimens. Figure 11 shows the results, together with some obtained by Holden (1976).

The experimental results agree well with the curves of Biarez and Gressillion (1972) and Janbu and Senneset (1974) for $0 > \beta > -15^0$, where β is a measure of the extent of the failure zone beneath the penetrometer. Meyerhof's (1976) relationship between ϕ and q_c also gave excellent estimates for $\sigma'_v < 200$ kPa, but at higher stresses ϕ was overestimated by up to three degrees.

CONCLUSIONS

Cone resistance, q_c, is a function of sand density and vertical (or lateral) effective stress. Friction Ratio, R_f, is a relatively insensitive parameter of little use in the accurate prediction of sand mechanical properties.

The one dimensional modulus of compressibility, M_o, has a lower bound of 3 q_c for the normally consolidated sand, and an average value of 12 q_c for the overconsolidated state.

The angle of shearing resistance, ϕ, can be determined with reasonable accuracy, for normally consolidated sands, from cone penetration resistance.

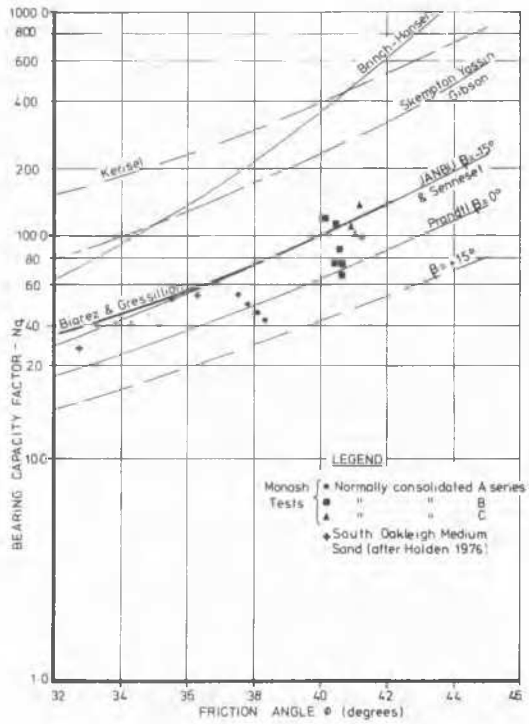

Fig. 11 Relationship between ϕ and N_q.

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