Schnaid, F. & Houlsby, G. T. (1994). *Géotechnique* **44**, No. 3, 529–532

DISCUSSION

Measurement of the properties of sand in a calibration chamber by the cone pressuremeter test

F. SCHNAID and G. T. HOULSBY (1992). *Géotechnique* **42**, No. 4, 587–601

M. Manassero, *Ingegneria Geotecnica, Torino, and Technical University of Torino*

The possibility of using experimental techniques to combine the tip cone resistance q_c and the pressuremeter limit pressure ψ_1 to estimate horizontal effective stress σ_h' in natural deposits with particular reference to sandy soils is interesting (Schnaid & Houlsby, 1990; Manassero, 1991). The complex mechanical behaviour of the actual granular media means that it may not be possible to find a fully reliable theoretical expression for σ_h' plotted against ψ_1, q_c and σ_v'. The only possibility of estimating σ_h' by way of ψ_1 and q_c therefore is to attempt empirical relationships with the related coefficients based on the fitting of the experimental results. It is, from this point of view, useful to add and compare experimental test results of research on different sands.

By using the q_c results from cone penetration tests and ψ_1 from the extrapolation of self-boring pressuremeter test results carried out in a calibration chamber on Ticino sand (Baldi, Bellotti, Ghionna, Jamiolkowski & Pasqualini, 1986; Ghionna, Jamiolkowski & Manassero, 1990), it is possible to estimate σ_h' using equation (6).

The ψ_1 values derived from the self-boring pressuremeter test by Ghionna *et al.* (1990) have been corrected for L/D ratios using equation (2) to be consistent with the Authors' data (see Fig. 12). By plotting, on Fig. 14, the estimated σ_h' values from Ticino sand test results against σ_h' applied in the calibration chamber (see Fig. 16), satisfactory agreement can be observed, with a scatter comparable to the Authors' data.

Manassero (1991) proposed alternative approaches for estimating σ_h' by combining q_c and ψ_1. The best results seem to come from the following equation, which takes into account not only q_c and ψ_1 but also the acting effective vertical stress σ_v'

$$A \frac{\sigma_h'}{\sigma_v'} \left[\frac{3q_c}{\sigma_v'(1 + 2\sigma_h'/\sigma_v')} \right]^B - \frac{\psi_1}{\sigma_v'} = 0 \qquad (7)$$

where $A = 2{\cdot}57$, $B = 0{\cdot}358$ and ψ_1 is the limit pressure from the self-boring pressuremeter test corrected using equation (2).

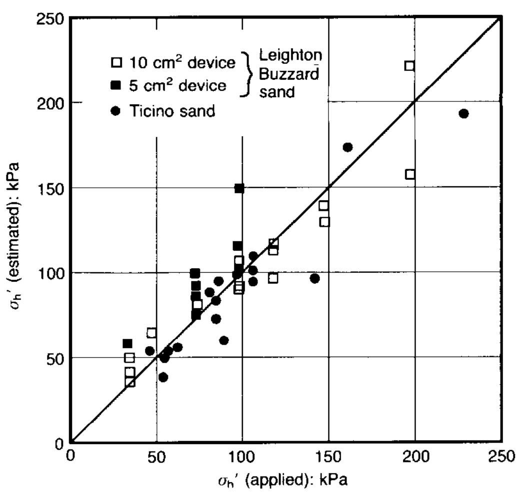

Fig. 16. Estimated and applied horizontal stress in the calibration chamber from equation (6)

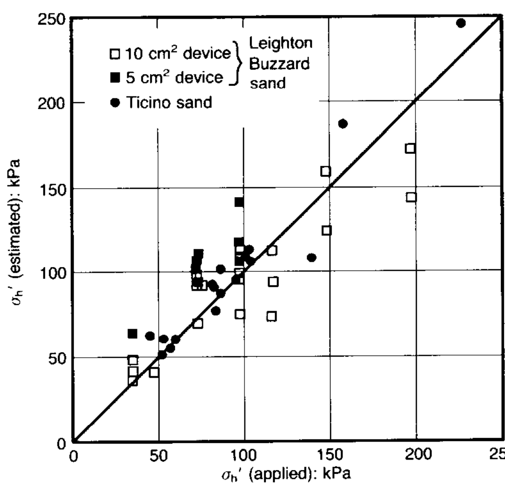

Fig. 17. Estimated and applied horizontal stress in the calibration chamber from equation (7)

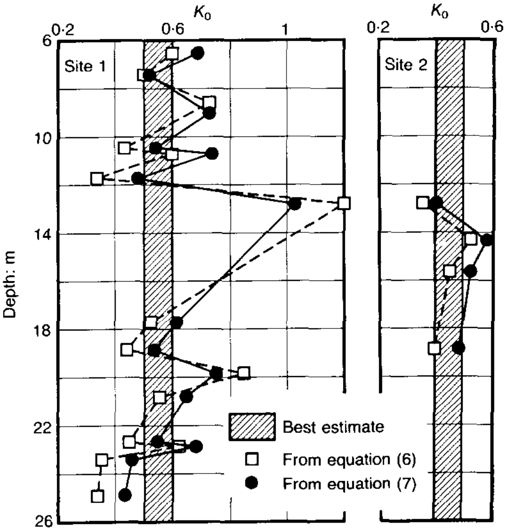

Fig. 18. Comparison of K_0 estimated in natural deposits

Estimated versus applied σ_h' results are plotted in Fig. 17, which shows that, even when using equation (7), σ_h' evaluated using results from tests on both Ticino sand and Leighton Buzzard sand is in good agreement with σ_h' applied in the calibration chamber. Moreover, Fig. 17 shows an acceptable scatter of results.

Figure 18 shows K_0 estimated from both equations (6) and (7) using in situ cone penetration tests and self-boring pressuremeter tests carried out in two natural sand deposits (Bruzzi, Ghionna, Jamiolkowski, Lancellotta & Manfredini, 1986; Ghionna, Braga & Macchi, 1993; Manassero, 1991). The best estimates of K_0, from both the geological history of the deposit and laboratory tests on undisturbed samples of silty clay lenses, are also shown for comparison. In spite of a rather large scatter, the K_0 general trends from both equations (6) and (7) seem to be promising.

Authors' reply

Although the Paper was about the application of the cone pressuremeter to the measurement of the properties of sand, we are interested in Mr Manassero's approach in which he combines measurements from the cone penetration test and the self-boring pressuremeter, and then interprets the results using similar methods to those adopted in the Paper. The cone penetration test results will be directly comparable with those obtained using the cone pressuremeter, but caution must be expressed about the interpretation of data from the self-boring pressuremeter in the same way as data from the cone pressuremeter.

Mr Manassero makes a correction for the different length to diameter ratios of the two devices, using the approximate expression suggested in the Paper. In the Paper this correction is intended for cone pressuremeters of different length to diameter ratios, and its applicability to self-boring pressuremeters is uncertain. Caution should also be expressed about the direct comparison of the measured limit pressure in the cone pressuremeter test, and the limit pressure obtained from the self-boring pressuremeter test using the method of Ghionna *et al.* (1990). The former represents an approximately constant value which is attained during the later stages of the cone pressuremeter test, which is capable of hoop strains of more than 30%. The latter is an extrapolation, using a theoretical techique, from test data which will usually involve hoop strains of less than 15%. The values obtained from the two tests would be expected to be related but not identical.

The quality of the estimation of horizontal stress in Fig. 16 is therefore pleasingly good, bearing in mind the possible differences in limit pressure. The form of equation (6), which was based on equations (1) and (3), is not considered by us to have any particular merit by comparison with other possible forms of equation. Equation (7) could be rewritten as

$$\frac{\psi_l}{\sigma_h'} = A\left(\frac{q_c}{p'}\right)^B \tag{8}$$

and could also be used to deduce σ_h' values from ψ_l and q_c. The fact that equation (7) requires knowledge of the vertical stress is not, in practice, a disadvantage, although the fact that it has to be solved iteratively for the σ_h' value is a minor inconvenience. The comparable success of equations (6) and (7) in predicting the horizontal stress indicates that, although expressed in different functional forms, these equations represent similar relationships.

The tests on Leighton Buzzard quartz sand have now been supplemented by tests on the Hokksund feldspathic sand and the Dogs Bay carbonate sand. Although the previous correlations fit the behaviour of these materials reasonably well, the best fit has been found by adjusting the coefficients slightly in equation (1)

$$\frac{q_c - \sigma_h}{\psi_l - \sigma_h} = 3{\cdot}39 + 0{\cdot}104R_d \tag{9}$$

This expression is shown as the straight line in Fig. 19, where it is compared with data, including Mr Manassero's data on Ticino sand. The linear

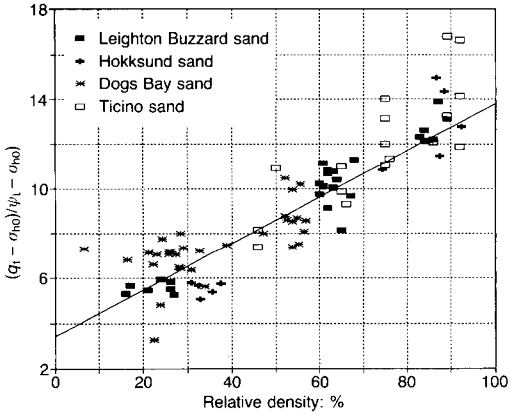

Fig. 19. Cone resistance divided by limit pressure plotted against relative density for different sands in calibration chambers

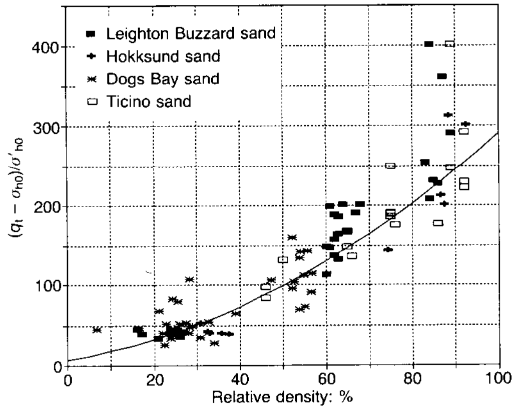

Fig. 21. Normalized cone resistance plotted against relative density for different sands in calibration chambers

relationship between relative density and q_c/σ_h' has been replaced by a linear relationship between relative density and ψ_l/σ_h'

$$\frac{\psi_l - \sigma_h}{\sigma_h'} = 1{\cdot}98 + 0{\cdot}191R_d \tag{10}$$

This relationship is shown in Fig. 20, again including a comparison with Manassero's data. Further details of the new data are given by Houlsby & Nutt (1992) and Nutt (1993). The implications of this are a quadratic relationship between q_c/σ_h' and relative density

$$\frac{q_c - \sigma_h}{\sigma_h'} = 6{\cdot}71 + 0{\cdot}853R_d + 0{\cdot}0199R_d^{\,2} \tag{11}$$

which is shown as the curve in Fig. 21. The horizontal stress can again be estimated by solving a quadratic, but this takes a slightly different form from equation (6)

$$\begin{aligned}&\sigma_h'^2(B + D + AD - BC)\\ &\quad + \sigma_h'(BC\psi_l - AD\psi_l - 2D\psi_l - Bq_c)\\ &\quad + D\psi_l^{\,2} = 0\end{aligned} \tag{12}$$

where $A = 1{\cdot}98$, $B = 0{\cdot}191$, $C = 3{\cdot}39$ and $D = 0{\cdot}104$.

The applied horizontal effective stresses are compared with those estimated from equation (12) in Fig. 22. Equation (12) has also been used to estimate the in situ horizontal stresses for the two sites used in Fig. 18. The trends are almost the same, although equation (12) results in slightly greater scatter about the estimated K_0 profile than equation (7).

It is emphasized, however, that much of this discussion relates to points of detail: in principle the approaches used by Mr Manassero and in the

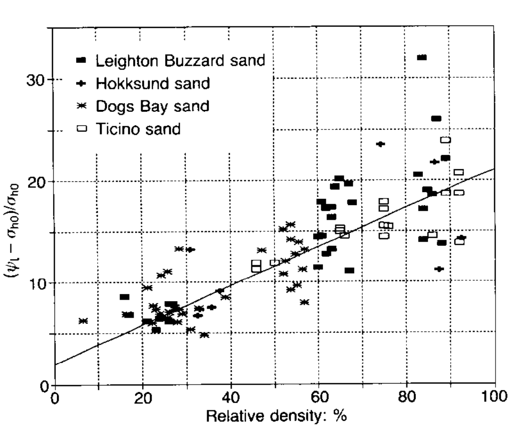

Fig. 20. Normalized limit pressure plotted against relative density for different sands in calibration chambers

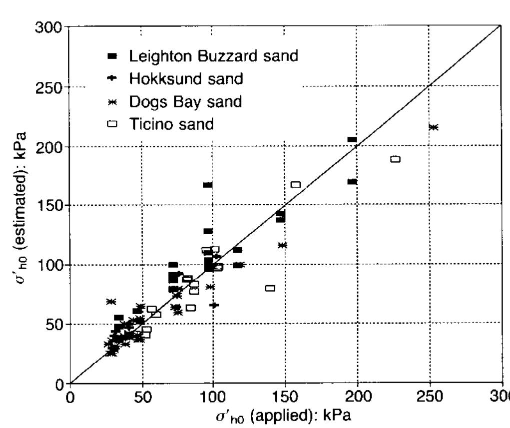

Fig. 22. Applied and estimated horizontal stresses in calibration chambers for different sands

Paper are similar. Both exploit the fact that the limit pressure in a pressuremeter test and the cone tip resistance from the cone penetration test depend in part on the horizontal stress. The results can therefore be combined in a way that allows the horizontal stress in the field to be estimated. The Paper takes this operation one stage further, and exploits the fact that the two measured quantities also depend on the relative density, so that it too can be deduced from the measurements.

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