Bolton, M. D., Gui, M. W., Garnier, J., Corte, J. F., Bagge, G., Laue, J. & Renzi, R. (1999). *Géotechnique* **49**, No. 4, 543–552

TECHNICAL NOTE

Centrifuge cone penetration tests in sand

M. D. BOLTON,* M. W. GUI,* J. GARNIER,† J. F. CORTE,† G. BAGGE,‡ J. LAUE§ and R. RENZI‖

KEYWORDS: centrifuge modelling; *in-situ* testing; laboratory tests; piles; sands.

INTRODUCTION

Centrifuges have been widely adopted in modelling geotechnical problems because, without the expense and delay of doing full-scale tests, the behaviour of a foundation can be observed in a soil specimen of known parameters. The most important feature of centrifuge tests is the simulation of self-weight to replicate full-scale stresses. The parameters are dependent on the effective stress level; therefore, in order to determine soil parameters relevant to models, in-flight tests such as the cone penetration test (CPT) must be carried out. The importance of miniature soil probes for model tests has been reviewed by Corte *et al.* (1991) and Bolton *et al.* (1993). There are two main uses for a CPT in the centrifuge: to check the uniformity or repeatability of the specimen and, more ambitiously, to obtain some absolute measure of the continuous in-flight strength profile of the specimen.

Different centrifuge centres have used different in-flight miniature probes of different diameters and materials under various test protocols. More recently, miniature CPTs have formed one component of a collaboration entitled 'European Programme of Improvement in Centrifuging' (EPIC), established between five European centrifuge centres: Cambridge University Engineering Department (CUED), UK; the Technical University of Denmark (formerly Danmarks Ingeniorakademi) (DIA), Lyngby, Denmark; the Istituto Sperimentale Modelli e Strutture (ISMES), Bergamo, Italy; the Laboratoire Central des Ponts et Chaussées (LCPC), Nantes, France; and Ruhr-Universität, Bochum (RUB), Germany. The aim of this paper is to report on both the random and the consistent variations which have been observed with CPTs in sand when identical prototypes have been modelled in the different laboratories.

SAND BEHAVIOUR RELEVANT TO CPT

It is well known (Jamiolkowski *et al.*, 1985) that the key parameters controlling cone resistance are the relative density I_D, the effective stress level σ'_v and the compressibility. Soil compressibility can be related to grain crushing and rearrangement. Fig. 1 compares the gradation curves of Fontainebleau sand and the finer material produced in CPTs performed at a centrifuge acceleration of $70g$. Bolton & McDowell (1997) have shown that the dispersion of particle sizes always increases with crushing, and associate this phenomenon with plastic volume reduction. It is also known that similar parameters, I_D, the mean effective stress p' and an index of aggregate crushing strength, also control the strength and dilatancy of sand observed in simple triaxial tests (Bolton, 1986).

The task, therefore, is to recognize the fundamental effects of density and stress on cone resistance measured in centrifuge tests with various boundary conditions, test locations, particle sizes and geometry effects.

INTERPRETATION OF CENTRIFUGE RESULTS

Fontainebleau sand was used in this series of tests. It is a uniform silica sand which consists of fine and rounded particles with an average (five laboratories) mean particle size d_{50} of 0·22 mm. The sand has an average uniformity coefficient of 1·3. The average maximum and minimum dry densities of the sand were found to be 1681 and 1415 kg/m^3, respectively. The specimen density was obtained by measuring the volume and the total weight of the soil or by embedded calibration boxes. Some general descriptions of the tests are presented in Table 1.

As pointed out by Schofield (1980), the radial acceleration field in the centrifuge will inevitably

Manuscript received 16 July 1998; revised manuscript accepted 11 December 1998.

Discussion on this technical note closes 5 November 1999; for further details see p. ii.

* University of Cambridge.

† Laboratoire Central des Ponts et Chaussées, Nantes.

‡ Technical University of Denmark, Lyngby.

§ Ruhr-Universität, Bochum.

‖ Istituto Sperimentale Modelli e Strutture, Bergamo.

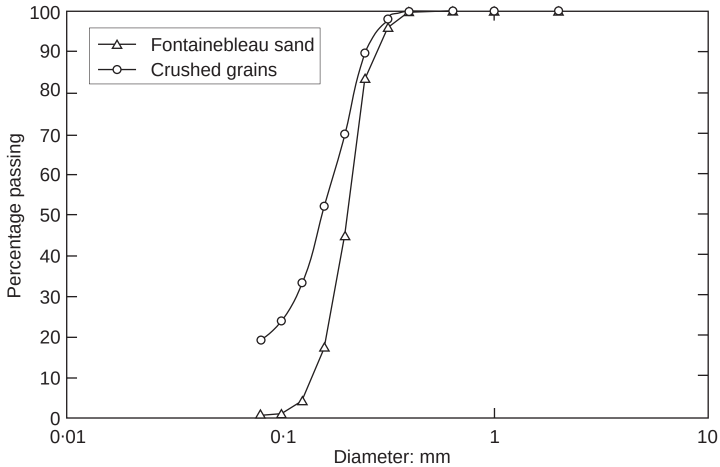


Fig. 1. Gradation curves of Fontainebleau sand before and after a CPT at 70 *g*

Table 1. General test configurations for various laboratories

Laboratory	CUED	DIA	ISMES	LCPC	RUB
Container*	C	C	C	R	C
Size: mm	210, 850	530	400	1200 × 800	100, 750
Method†	H	A	A	A	H
Cone diameter: mm	10	12	11·3	12	11·3
Average radius to surface R: mm	3755	2295	1840	5117	3780

* R, rectangular, C, cylindrical.
† A, automated full-width pluviation; H, hand pluviation by way of a hose and hopper.

cause some non-linear stress variation with depth. In order to overcome this problem, all the measurements of depth of penetration (referred to the tip of the cone), which are recorded through a linear potentiometer, are transformed to a corrected prototype depth z_{pc} as follows:

$$z_{pc} = Nz\left(1 + \frac{z}{2R}\right) \quad (1)$$

where z is the model penetration depth, R is the radius of the surface of the specimen from the central axis of the centrifuge and N is the test acceleration level at the surface. For dimensional analysis, the cone resistance is normalized with respect to the overburden pressure, and the penetration depth is normalized with respect to the cone diameter. The normalized cone resistance Q and normalized penetration depth Z are given in equations (2) and (3) below:

$$Q = \frac{q_c - \sigma_v}{\sigma'_v} \quad (2)$$

$$Z = \frac{z}{B} \quad (3)$$

where σ_v and σ'_v are the total and effective stresses, respectively, and B is the diameter of the cone.

Prior to the investigation, each laboratory was required to perform two exploratory tests so that the repeatability of interlaboratory tests could be compared. It was found that the interlaboratory variation between CPT profiles for dense sand (average $I_D = 84\%$) fell within a ±10% band width (Fig. 2) (Renzi *et al*., 1994). Part of this observed scatter may be explained by differences in the methods used for preparing the sand samples (Table 1) and in the densities obtained. Profiles taken in a single laboratory are even more repeatable, as shown in Fig. 3, where the strength discrepancies are shown to be broadly consistent with the measured density variations.

The double-curvature CPT profile, obtained in centrifuge tests from each laboratory (Fig. 3) and especially the low value measured at shallow

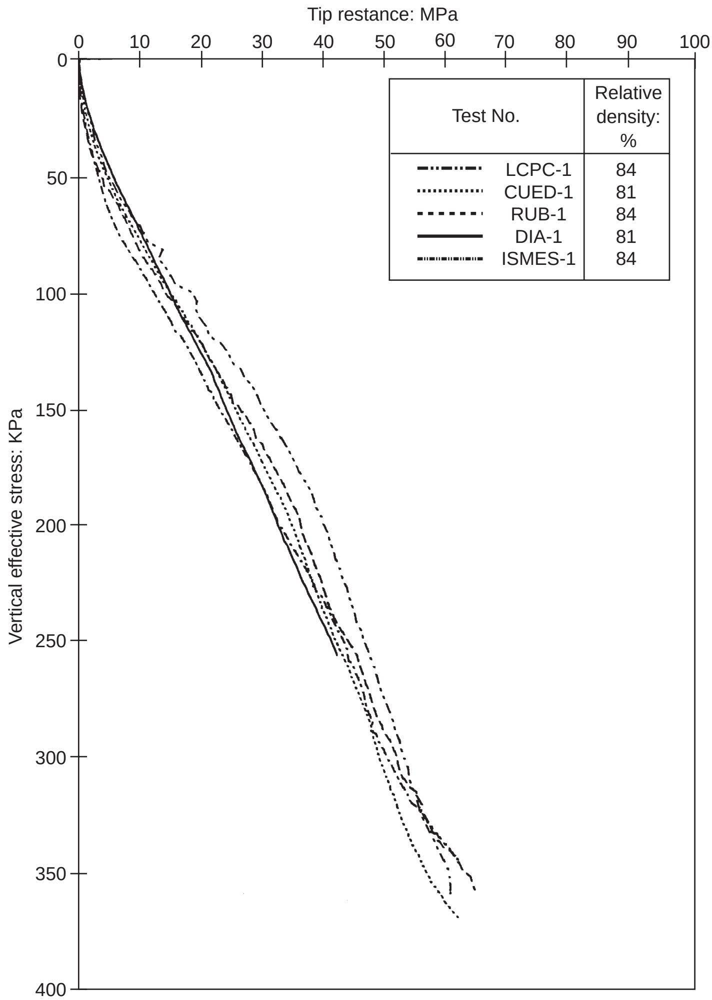


Fig. 2. Repeatability of CPT results among five laboratories

depths make it difficult to assess variations in density in a model, or between models. The normalization of the Q and Z axes makes the interpretation more reliable, and the outcome of this transformation of Fig. 2 is given in Fig. 4.

DIMENSIONAL ANALYSIS OF CPT PARAMETERS

Bolton *et al.* (1993) proposed to use dimensional analysis to interpret CPT results obtained from centrifuge tests. Since all the tests were performed in Fontainebleau sand, intrinsic parameters such as the angle of shearing resistance at constant volume ϕ'_{crit}, the elastic stiffness G_{m}, the characteristic fracture strength of a grain ϕ'_{c} and the ratio of the cone diameter to the mean grain size B/d_{50} all remain constant. For a particular relative density I_{D}, we are then able to group all the other factors that may affect the normalized cone resistance Q in a non-dimensional group as in equation (4) below:

$$Q = \frac{q_{\mathrm{c}} - \sigma_{\mathrm{v}}}{\sigma'_{\mathrm{v}}} = f\left(\frac{\sigma'_{\mathrm{v}}}{\sigma'_{\mathrm{c}}}, \frac{z}{B}, \frac{D}{B}, \frac{S}{B}, \frac{B}{d_{50}}, \text{ etc.}\right) \tag{4}$$

where D and S refer to the geometry of the test (D is the container diameter, and S is the distance from the nearest wall boundary to the location of penetration).

D/B: container size effect

The effect of the container-to-cone diameter ratio (D/B) was studied by performing CPTs in

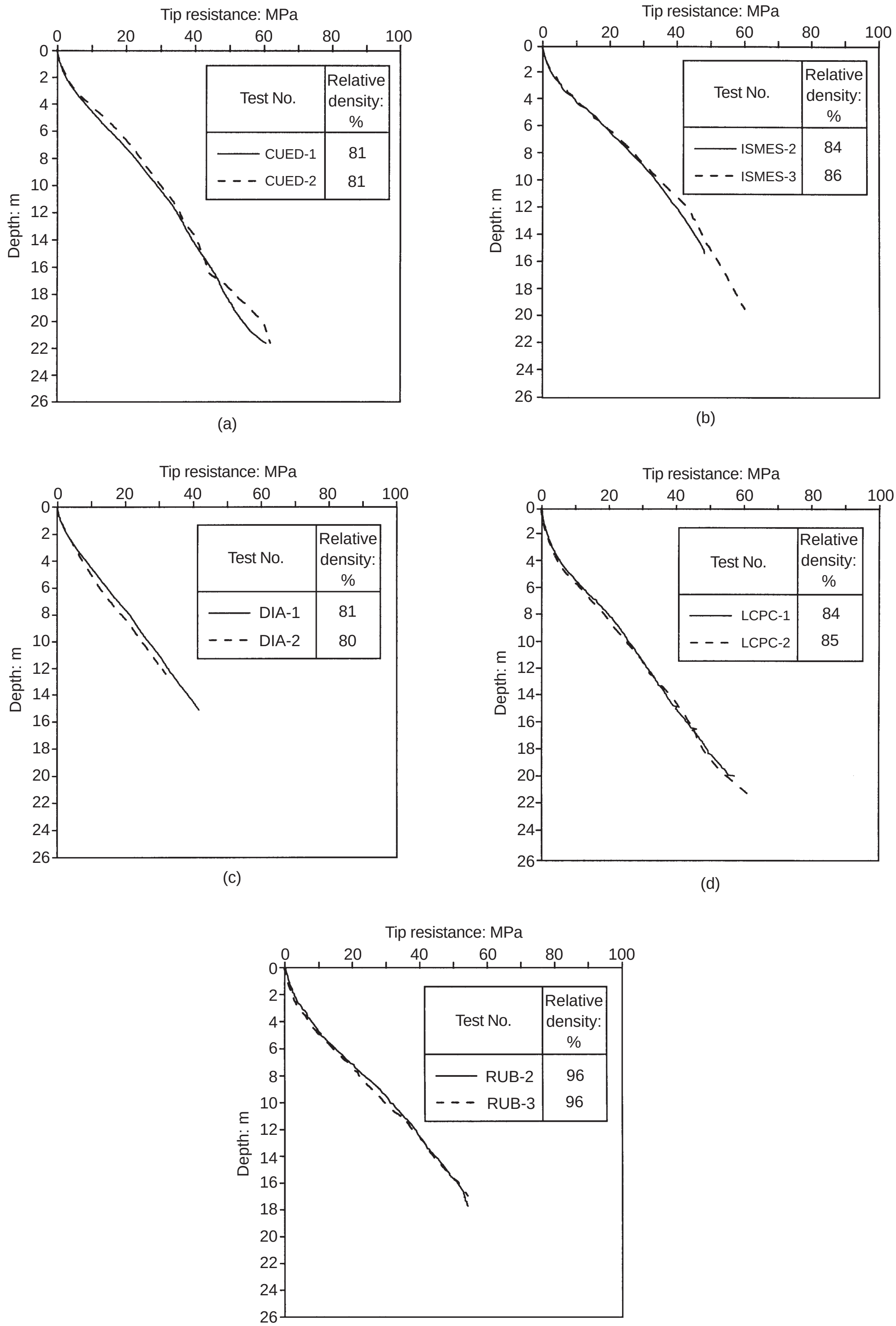


Fig. 3. Repeatability of CPT results for each laboratory

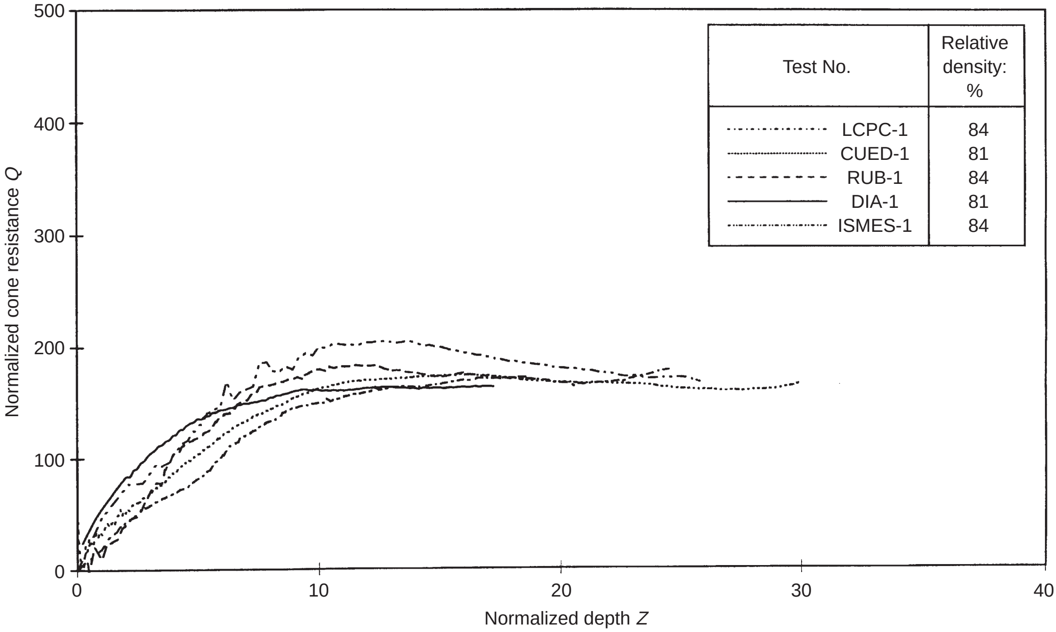


Fig. 4. Normalized cone resistances for five laboratories

containers with various diameters. For CPTs using a 10 mm dia. cone, containers of 850 and 210 mm dia. were used, while for 12 and 11·3 mm dia. cones, containers of 530 and 100 mm dia. were used. This gives different D/B ratios, ranging from 85 to 8·85. Fig. 5 reveals that for dense sand, there is no apparent increase in Q for a test done with $D/B = 44$ and $D/B = 85$. However, Q is significantly larger for the test carried out in the container with $D/B = 8{\cdot}85$.

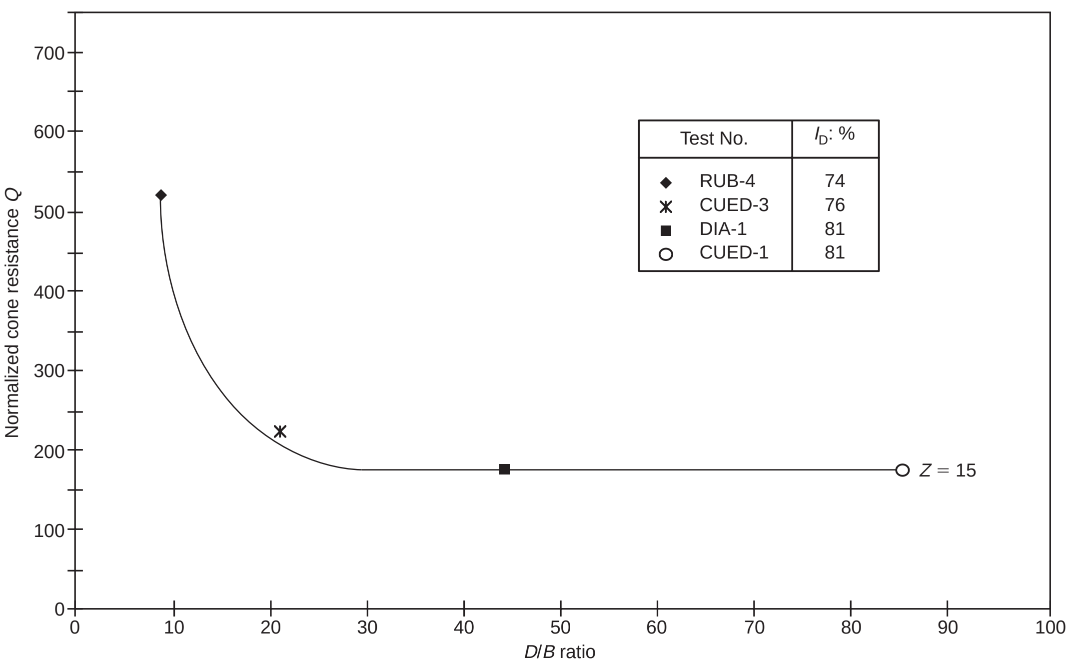


Fig. 5. Effect of D/B ratio

S/B: side boundary effect in rectangular container

This effect was studied by performing CPTs in a 1200 mm × 800 mm rectangular box using a 12 mm dia. cone. Dense ($I_D = 91\%$) and medium dense ($I_D = 58\%$) specimens were prepared. The ratio S/B of the distance of the test from the nearest wall to the cone diameter ranges from 33 to 2. A penetrometer which could be moved in flight was used. The results of the tests are plotted in Fig. 6. For dense sand, there is an average increase in Q of about 30% for a test performed at $S/B = 2$ as compared to a test done at $S/B = 33$. For a medium dense sand, the increase was, empirically, more significant than with the dense specimen. An increase of 35% was observed for a test performed at $S/B = 2$ compared to a test done at $S/B = 33$.

S/B: side boundary effect in circular container

The S/B effect was also studied in a 530 mm dia. container. Two dense specimens, with I_D of 81% and 80%, respectively, were prepared. As for the rectangular container, a cone penetrometer which could be moved in flight was used. Three CPTs were conducted for each specimen and the results are presented in Fig. 7. It was found that for a circular container, there is no significant deviation in Q, for both $S/B = 11$ and $S/B = 22$.

Note that for the first specimen, the test was conducted at the centre of the specimen, and subsequently the penetrometer was moved to the quarter-points of the container. For the second specimen, the first and second penetration tests were conducted at the quarter-points, and the final tests at the centre of the specimen. The results reveal that the order of the tests has no apparent effect on the measured cone resistance.

B/d_{50}: particle size effect

The effect of the ratio of the cone diameter to the mean grain size (B/d_{50}) was studied by Bolton *et al.* (1993) on Leighton Buzzard sand. For fine sand at a single relative density, the normalized cone resistance Q is plotted against the normalized depth Z for cones of different diameters in Fig. 8(a). It is necessary to preserve a constant stress level σ'_v/σ'_c for the different cones. Now

$$\sigma'_v = \rho_{dry} gzN \tag{5}$$

where ρ_{dry} is the dry density; equation (5) can be rewritten as

$$\sigma'_v = \rho_{dry} g \left(\frac{z}{B}\right) NB \tag{6}$$

so it is necessary to keep NB constant in order to preserve a constant σ'_v for each value of z/B. Each test therefore modelled a single prototype cone, 0·4 mm in diameter in this case. Fig. 8(a) shows that the data from this modelling-of-models trial

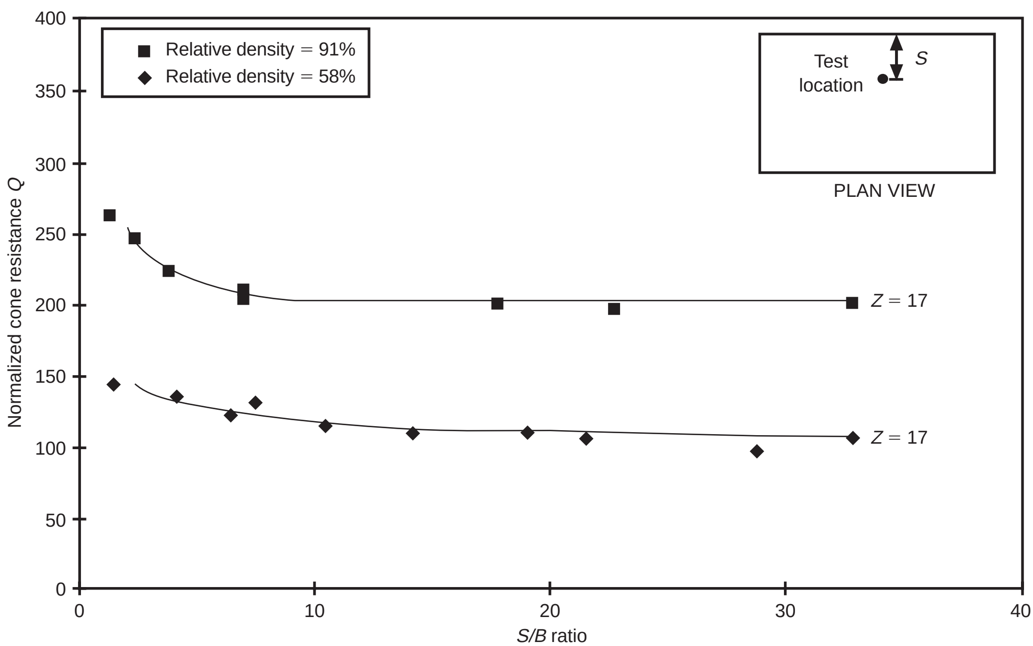


Fig. 6. Effect of S/B ratio in rectangular container

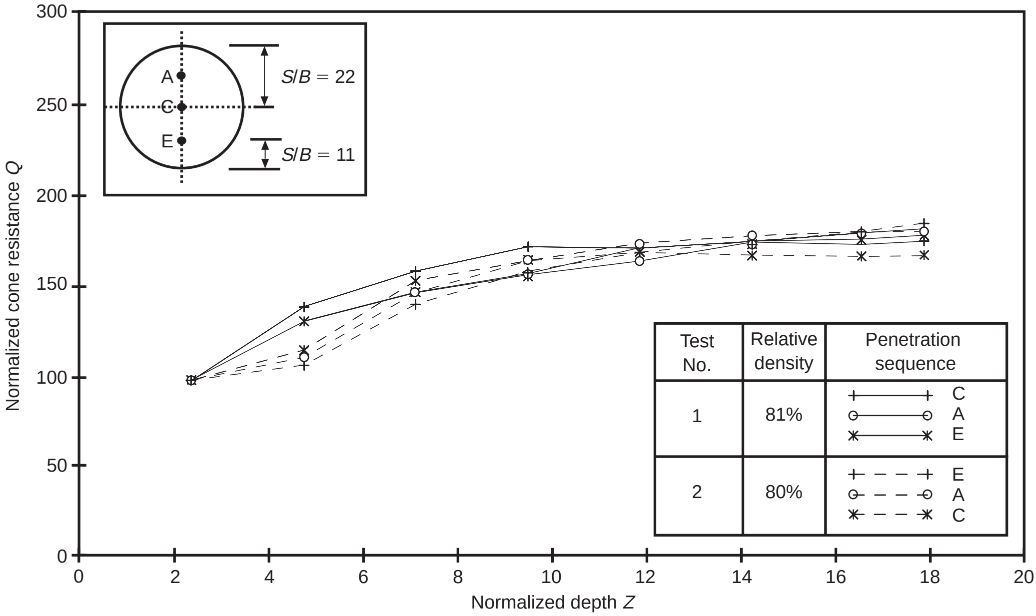


Fig. 7. Effect of S/B ratio in circular container

are nicely superimposed until each cone approaches the base of the test container. This proves that the soil particle size does not affect the result for values of the ratio B/d_{50} in the range 28 to 85.

Figure 8(b) shows a similar plot medium and coarse Leighton Buzzard sand. Treating each soil separately, the plots for the medium sand merge reasonably well for $B/d_{50} = 48$ and 25, but there is a suggestion of a small amount of extra resistance at $B/d_{50} = 16$. For coarse sand, all the data are somewhat higher and, while there is little evidence of distortion on reducing B/d_{50} from 21 to 11, it can be seen that a further reduction to 7 does raise the resistance, especially at shallow depths. Some extra resistance must therefore be anticipated if the B/d_{50} ratio is to be permitted to fall below about 20.

σ'_v/σ'_c: *stress level effect*

The most reliable way to investigate level effects is to plot Q against Z holding B/d_{50} constant, for a particular soil at a particular density, but to test at different acceleration ratios N. Three CPTs were performed under the same boundary conditions at three elevated g levels, 40 g, 70 g and 125 g. All the tests were performed using the same 11·3 mm dia. cone in specimens with $I_D = 96\%$. Fig. 9 shows that as the stresses rise, the values of Q fall, presumably owing to the enhanced tendency for crushing, since there is no evidence to show that the fall is caused by side friction. It is clearly necessary to account separately for crushing and relative density, as already demonstrated by Jamiolkowski *et al*. (1985) for deep probes.

Other effects

Small, and generally negligible, effects were obtained in dry sand by increasing the penetration rate from 2·5 mm/s to 20 mm/s, and by preconsolidation of the sand to an overconsolidation ratio of 2.

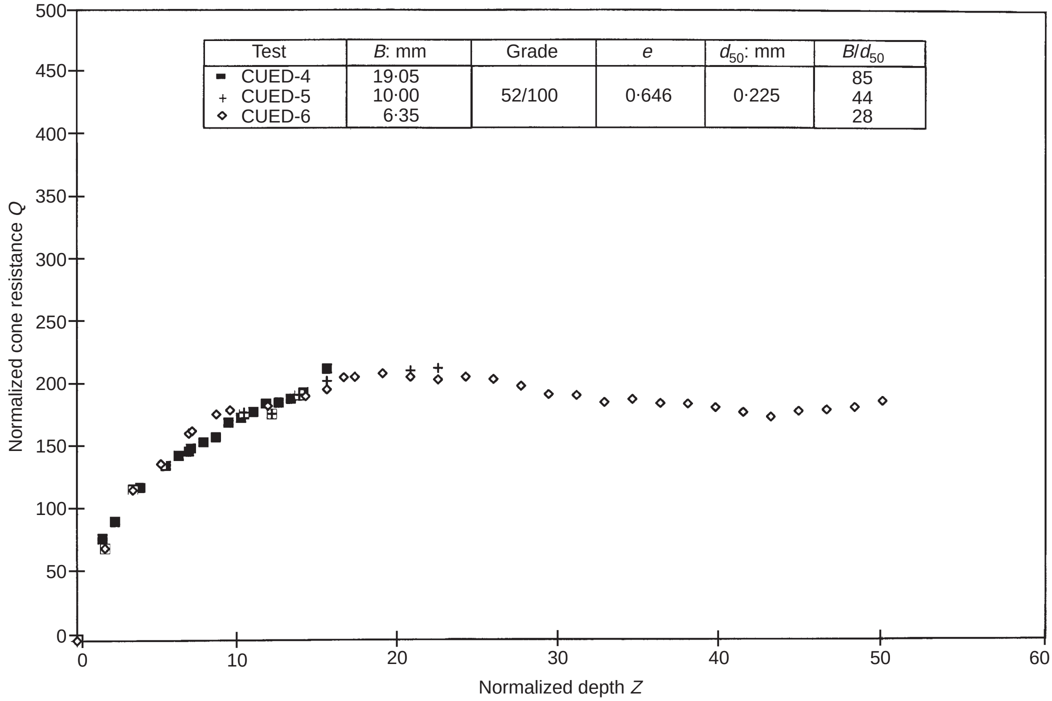
DISCUSSION

Probe size

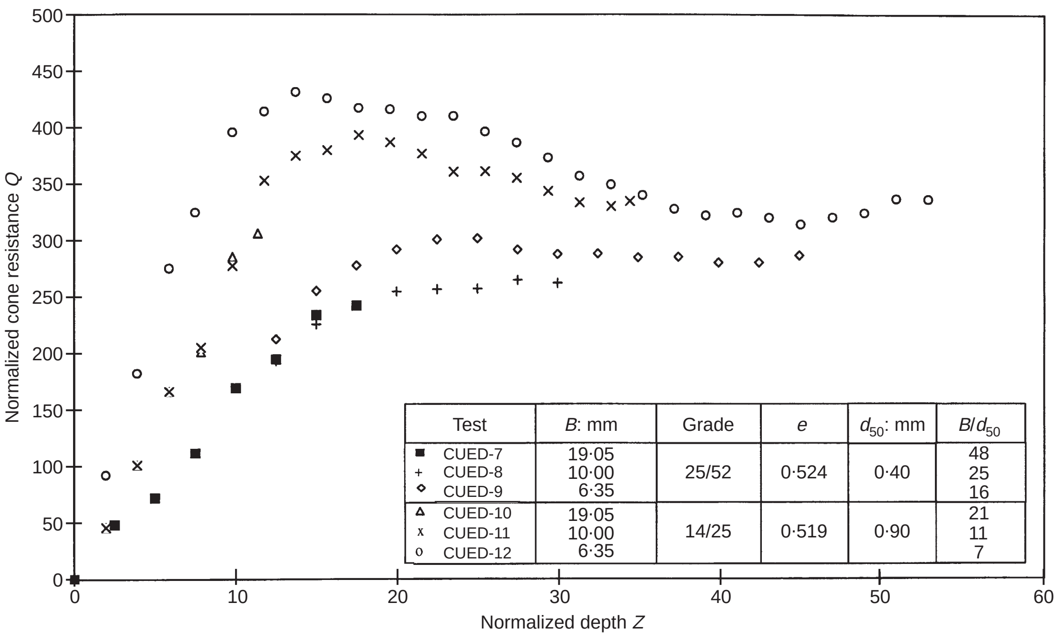
In order to achieve an unbiased result, the cone diameter B should be at least twenty times greater than the mean particle diameter d_{50}. If a smaller cone is to be adopted, some further investigations must be carried out, for example by checking with an even smaller cone to demonstrate there is no difference in results.

Interference

In any container, a CPT should be performed at least $10B$ away from any hard boundary. If there is a need to conduct a test very close to a hard boundary, a membrane with the right stiffness could be used to simulate an infinite boundary condition, but its selection is difficult (Gui, 1995).



(a)



(b)

Fig. 8. Grain size effects in Leighton Buzzard sand: (a) fine particles; (b) medium and coarse particles

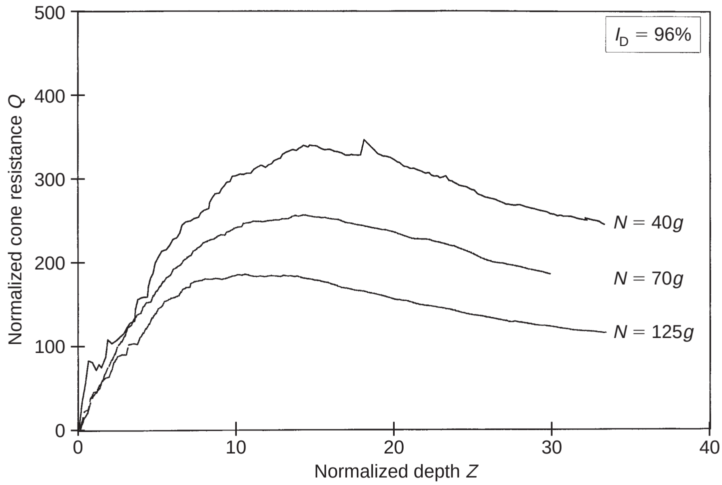


Fig. 9. Effect of stress level

Geometry effect

It is clear that there are two phases of behaviour, depending on the depth ratio Z (Gui & Bolton, 1998). Shallower than some critical ratio ($Z = 10$ in Fig. 4), the coefficient Q increases with depth ratio in the fashion of shallow foundations. Deeper than this critical depth, the coefficient seems to hold steady and then to fall slightly, which is a characteristic of deep foundations.

The boundary fringe, ten cone diameters wide, affecting every surface of a container whether free or fixed, creates a particular difficulty for model testers. Special calibrations have to be carried out if cone data from the fringe are to be meaningful. This reinforces the conclusion that cones should be as small as possible, consistent with $B/d_{50} > 20$.

Stress level effect

It has been seen from Fig. 9 that the bigger the initial stress level, the smaller the normalized cone resistance Q. Therefore, it is essential to find the correct prototype stress level when modelling the behaviour of piles or cone penetrometers. It has been possible, using centrifuge data, to discriminate properly between size effects and stress level effects.

CONCLUSIONS

The repeatability and reliability of CPTs in the centrifuge have been found to be very encouraging. CPTs can be used for clients as an indication of the absolute soil state for the purpose of proving similarity with the field, provided limitations are set on the boundary separations and the cone/grain diameter ratio. Guidelines and procedures have been proposed for avoiding any spurious effects and allowing comparisons between centrifuge CPTs carried out in different laboratories.

ACKNOWLEDGEMENT

The authors are grateful to the European Commission, who funded the above collaboration under EEC Science Contract SC1-CT91-0626, with J. F. Corte acting as the scientific coordinator.

REFERENCES

Bolton, M. D. (1986). The strength and dilatancy of sands. *Géotechnique* **36**, No. 1, 65–78.

Bolton, M. D., Gui, M. W. & Phillips, R. (1993). Review of miniature soil probes for model tests. *Proc. 11th South East Asia Geotech. Conf., Singapore*, 85–91.

Bolton, M. D. & McDowell, G. R. (1997). Clastic mechanics. *Proceedings of the IUTAM symposium on mechanics of granular and porous materials*, Cambridge, pp. 35–46.

Corte, J. F., Garnier, J., Cottineau, L. M. & Rault, G. (1991). Determination of model soil properties in the centrifuge. *Proceedings of the international conference on the centrifuge*, Boulder, Colorado, pp. 607–614.

Gui, M. W. (1995). *Centrifuge and numerical modelling of pile and penetrometer in sand*. PhD thesis, University of Cambridge.

Gui, M. W. & Bolton, M. D. (1998). Geometry and scale effects in CPT and pile design. *Proc. 1st Int. Conf. Site Characterization, Atlanta*, 1063–1068.

Jamiolkowski, M., Ladd, C. C., Germaine, J. T. & Lancellotta, R. (1985). Theme lecture: new developments in field and laboratory testing of soils. *Proc. 11th Int. Conf. Soil Mech. Found. Engng, San Francisco*, 57–156.

Renzi, R., Corte, J. F., Rault, G., Bagge, G., Gui, M. & Laue, J. (1994). Cone penetration tests in the centrifuge: experience of five laboratories. *Proceedings of the international conference on the centrifuge*, Singapore, pp. 77–82.

Schofield, A. N. (1980). Rankine lecture: Cambridge University geotechnical centrifuge operations. *Géotechnique*, **30**, No. 3, 227–268.