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Guidelines for cone penetration tests in sand

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ABSTRACT: A study of miniature cone penetration tests (CPTs) in centrifuge models has been undertaken by five European laboratories. It is demonstrated that CPTs conducted on the same soil type, with similar deposition and stress history, but performed in different laboratories, give similar data. Guidelines for the consistent use of these devices are developed, including the minimum acceptable ratios of container width to cone diameter and cone diameter to mean particle size, the minimum acceptable separation measured in cone diameters from a hard boundary or from a previous CPT, and the possible rates of penetration.

1 INTRODUCTION

Cone penetration tests (CPTs) have frequently been performed in the centrifuge in order 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) in UK; Technical University of Denmark (DIA, formerly Danmarks Ingeniorakademi of Lyngby in Denmark); Istituto Sperimentale Modelli e Strutture (ISMES) of Bergamo in Italy, Laboratoire Central des Ponts et Chaussees (LCPC) of Nantes in France; and Ruhr-Universitat (RUB) of Bochum in Germany.

The main objective of this paper is to report on the conclusions derived from the above collaboration. As a result, certain guidelines are proposed for the use of CPTs in centrifuge models.

2 INTERPRETATION OF CENTRIFUGE RESULTS

Fontainebleau sand was used in this series of tests. It is a uniform material 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. Specimen density was obtained by measuring the volume and the total weight of the soil or by embedded calibration boxes (Renzi et al, 1994).

Prior to the investigation, each laboratory performed two exploratory tests so that the repeatability of inter-laboratory tests could be compared. The geometry of the tests and method of specimen preparation for each laboratory are summarised in Table 1 and it was found that the inter-laboratory variation between CPT profiles (Fig 1) fell within a ±10% band width.

Table 1: Test configuration for various laboratory.

Laboratory	CUED	DIA	ISMES	LCPC	RUB
Container [1]	C	C	C	R	C
Size (mm)	210, 850	530	400	1200 x 800	100, 750
Method [2]	H	A	A	A	H
Cone Diameter (mm)	10	12	11.3	12	11.3
Avg. radius to surface (mm)	3755	2295	1840	5117	3780

[1] R: Rectangular, C: Cylindrical; [2] A: Automated full-width pluviation, H: Hand pluviation via a hose and hopper.

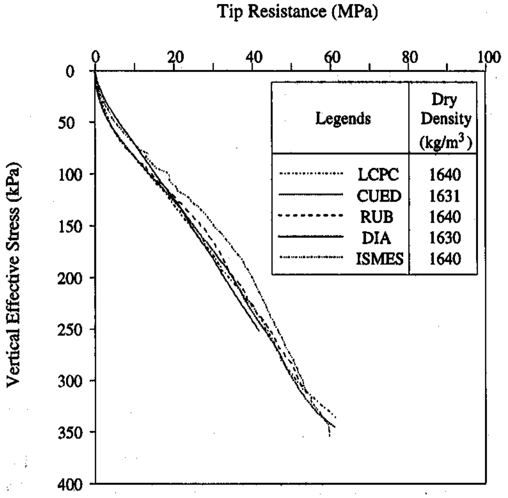

Fig 1: Repeatability of CPT results within 5 laboratories.

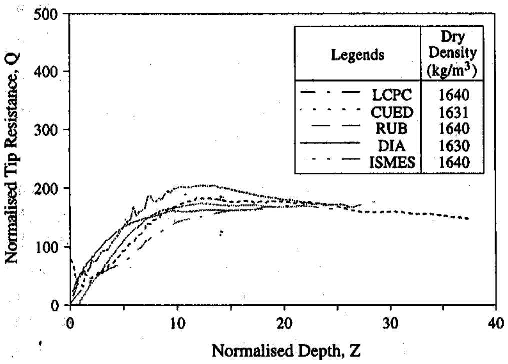

Fig 2: Normalised tip resistance within 5 laboratories.

For interpretation of CPT results, normalisation is adopted. The tip resistance q_c is normalised with respect to overburden pressure; and the penetration depth is normalised with respect to cone diameter. Normalised tip resistance Q and normalised penetration depth Z are given as follow:

$$Q = \frac{q_c - \sigma_v}{\sigma'_v} \tag{1}$$

$$Z = \frac{z}{B} \tag{2}$$

where σ_v and σ'_v are the total and effective stresses respectively, z is the model penetration depth; and B is the diameter of the cone. The normalisation of the axes Q and Z makes the interpretation more reliable, and the outcome of the transformation of Fig 1 is given in Fig 2.

3 DIMENSIONAL ANALYSIS OF CPT PARAMETERS

Bolton et al (1998) proposed to use dimensional analysis to interpret CPT results obtained from centrifuge tests. Since all the tests were performed in Fontainebleau sand, we are holding ϕ_{crit}, G_m, p'_c, and B/d_{50} constant (ϕ_{crit} is the angle of shearing at constant volume, G_m is the elastic stiffness, p'_c is the aggregate crushing strength and d_{50} is the mean particle diameter of the soil). For a particular relative density I_D, we are then able to group all the other factors that may affect the normalised tip resistance Q in non-dimensional group as:

$$Q = \frac{q_c - \sigma_v}{\sigma'_v} = f\left(\frac{\sigma'_v}{p'_c}, \frac{z}{B}, \frac{D}{B}, \frac{S}{B}, OCR\right) \tag{3}$$

where D is the container diameters, and S is the distance from the nearest wall boundary to the location of penetration. For detailed discussion, please refer to Bolton et al (1998).

3.1 *S/B effect in circular container*

The S/B effect has been studied in a 530 mm diameter container. Two dense specimens with ρ_{dry} of 1630 and 1627 kg/m³ respectively were prepared. A penetrometer which can be moved in-flight was used. Three CPTs were conducted for each specimen and the results are presented in Fig 3. It was found that for a circular container, there is no significant deviation in Q for both S/B=11 and S/B=22.

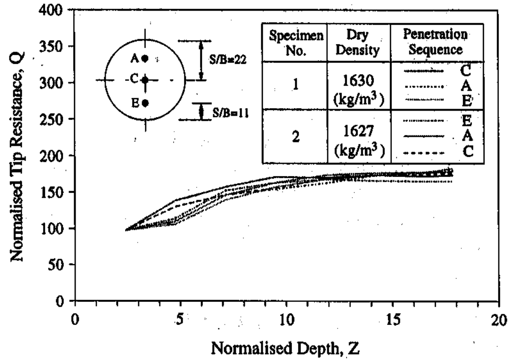

Fig 3: Effect of S/B ratio in circular container.

Also, 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 the second penetration tests were conducted at the quarter-point; and finally at the centre of the specimen. The results reveal that the order of the tests has no apparent effect on the measured tip resistance.

3.2 *S/B effect in rectangular container*

This effect was studied by performing CPTs in a 1200 x 800 mm^2 rectangular box using a 12 mm diameter cone. Dense (dry density ρ_{dry} = 1656 kg/m^3) and medium dense (ρ_{dry} = 1570 kg/m^3) 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 can be moved in-flight was used. The results of the tests are plotted in Fig 4. For both sand densities, there is an average increase of Q of about 35% for a test performed at S/B=2 as compared to a test done at S/B=33.

3.3 *D/B effect*

The effect of the container/cone diameter ratio (D/B) was studied by performing CPTs in containers with various diameters. For CPTs using a 10 mm diameter cone, containers of 850 and 210 mm diameters were used; while for 12 and 11.3 mm diameter cones, containers of 530 and 100 mm diameters respectively 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=85 and D/B=44. However, Q is larger for D/B=21 and significantly larger for D/B=8.85.

The apparent influence of container can only be explained on the basis that the steel shell increases the confining pressure induced around the plastic soil zone.

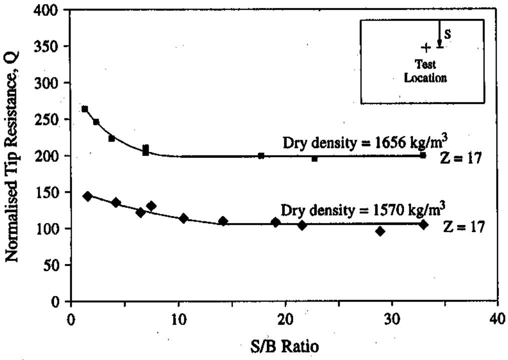

Fig 4: Effect of S/B ratio in rectangular container.

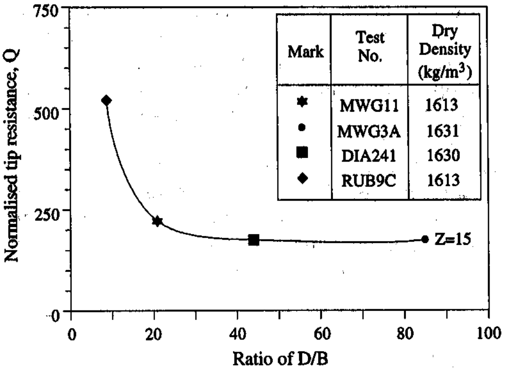

Fig 5: Effects of D/B

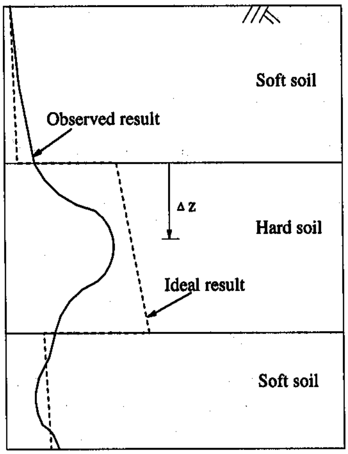

Fig 6: Effect of development on CPT profiles.

3.4 *Δz/B effect*

It has been suspected that a CPT will not be able to register the absolute tip resistance at the instant when it penetrates into a new soil layer, Fig 6.

After some distance, the observed tip resistance profile starts to deviate from the ideal profile before entering the hard soil layer because the cone is capable of detecting the hard boundary at a few cone diameters away. Once it enters the hard soil, "development" takes place prior to registering the true resistance of the hard soil (Gui & Bolton, 1998). Thereafter, the observed profile falls drastically because of the soft soil lying beneath it.

This has a significant impact if the resolution of a thin soil layer is important to the design. It is therefore important, at least qualitatively, to study the effect of the penetration depth (Δz) required to develop the resistance of a new soil layer.

A set of unusual cone uplift tests (Gui, 1995) was conducted in order to study the development of the full penetration resistance. The result reveals that it takes about 5 cone diameters of displacement to "develop" a uniformly graded sand ahead of an advancing probe, whichever direction it is travelling in (Fig 7). Detailed discussion can be found in Gui and Bolton (1998).

3.5 *B/d_{50} effect*

The effect of the ratio of the cone diameter to the mean grain size (B/d_{50}) has been studied by Bolton et al (1993) on Leighton Buzzard sand. For fine sand at a single relative density, normalised tip resistance Q is plotted against normalised depth Z for cones of different diameter in Fig 8(a). It is necessary to preserve a constant stress level σ'_v/p'_c for each value of z/B. Each test therefore modelled a single prototype cone of 0.4 m diameter. Fig 8(a) shows that the data from this modelling-of-models trial 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 the ratio B/d_{50} in the range of 85 to 28.

Fig 8(b) repeats the same plot for 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 insufficient evidence of distortion in reducing B/d_{50} from 21 to 11, it can be seen that a further reduction to 7 does raise resistance especially at shallow depths. Some extra resistance due to the loss of degrees of freedom must therefore be anticipated if B/d_{50} ratio is to be permitted to fall below about 20.

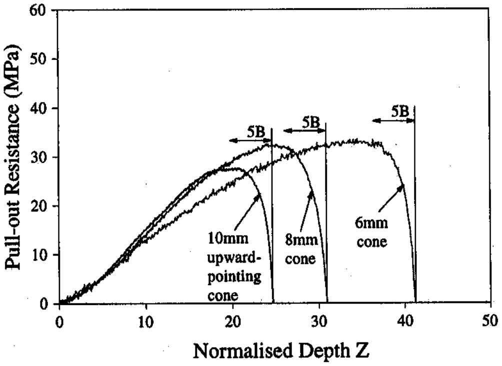

Fig 7: Mobilisation of upward pointing cones.

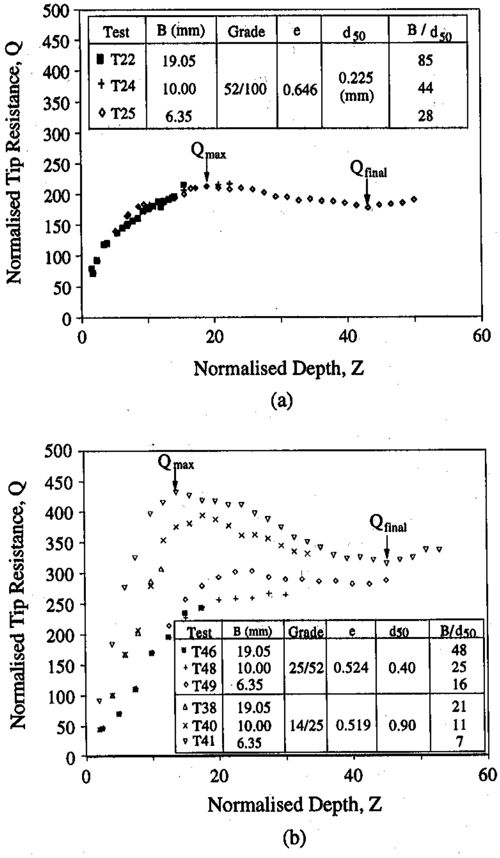

Fig 8: Grain size effects on Leighton Buzzard sand: (a) fine particles; and (b) medium and coarse particles. (Data from Lee, 1990)

3.6 *Penetration rate effect*

Five dense (ρ_{dry} = 1644 ± 4 kg/m^3) dry specimens were prepared in a 400 mm diameter container. One CPT was performed at the centre of each specimen using a 11.3 mm diameter cone. The rates of penetration were 2.5 and 20 mm/s. Although grain crushing might have been expected to introduce some rate effect, Fig 9 shows the effect is minimal.

3.7 *OCR effect*

Overconsolidation ratio is easy to investigate in the centrifuge, tests being repeated in identical circumstances at identical accelerations *N*, the soil

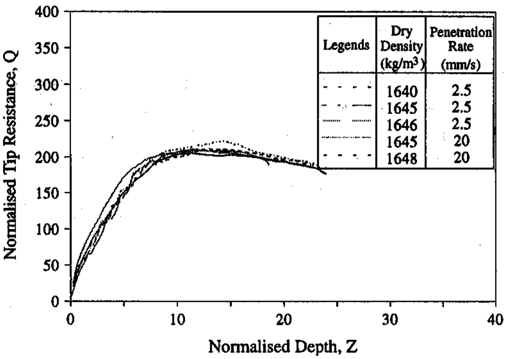

Fig 9: Effect of rate of penetration.

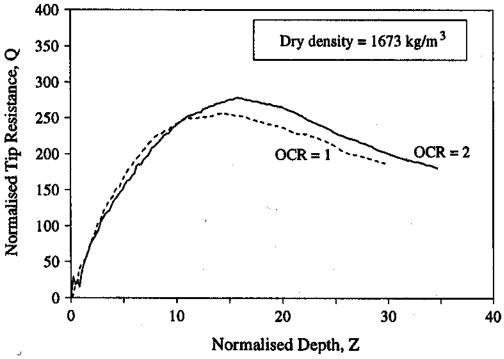

Fig 10: Effect of overconsolidation ratio.

having been previously raised to different maximum accelerations OCR x *N*.

Lee (1990) observed an overconsolidation effect in dense 25/52 Leighton Buzzard sand (d_{50}=0.40mm). However, in the fine and rounded Fontainebleau sand of OCR=2, Fig 10 shows that there is no apparent OCR effect on Q for Z<11. At greater depth, a 10% increase was observed for OCR=2, but is not very significant in the light of ±10% variability reported earlier. Obviously, preconsolidation would have more influence with more angular (eg. Leighton Buzzard sand) or more crushable sands.

3.8 *Stress level effect*

The most reliable way to investigate stress 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 have been performed under the same boundary condition at three elevated *g*-levels, 40, 70 and 125g. All the tests were performed using the same 11.3 mm diameter cone in specimens with ρ_{dry} of 1673 kg/m^3.

Fig 11 shows that as stresses rise, the values of Q fall, presumably due 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 in the correlation of Jamiolkowski et al (1985) for deep probes.

4 GUIDELINES FOR USE OF CPTS IN CENTRIFUGE TESTS

4.1 *Standardisation: Probe size*

In order to achieve an unbiased result, cone diameter B should be at least twenty times greater than the mean particle diameter d_{50}. The hypothesis of effective cone diameter (Gui & Bolton, 1998) divulges that if $B/d_{50}>20$, the error one could possibly get in Q is at most 10%. 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.

4.2 *Standardisation: Penetration rate*

Penetration rate has not been seen to be very important in this research. It is, however, possible to define the penetration rate at which drained or undrained tests are conducted (Bolton et al, 1998). Cone penetration in saturated soils induces excess pore pressures. If the rate of penetration is much faster than the rate of dissipation, the test will be undrained.

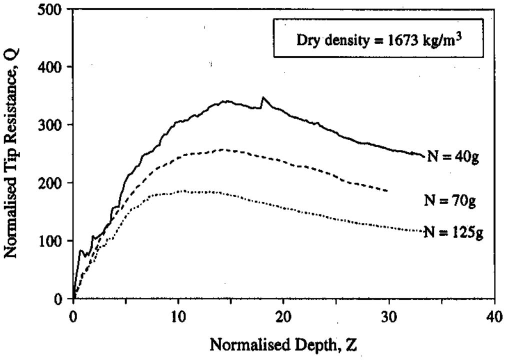

Fig 11: Effect of stress level.

4.3 *Resolution*

A 10 mm diameter cone has been found to be preferred in the field tests to the conventional 38 mm diameter cone (Power and Geise, 1995). If very fine details are wanted, smaller cones must be adopted because the cone must penetrate at least 5B before it fully develops the absolute value in any layer. Likewise, in model tests which commonly deploy 10 mm cones, a cone with smaller diameter will be able to provide a better definition of soil layers and will still indicate an unbiased penetration resistance, provided that ratio B/d_{50} is greater than 20.

4.4 *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 the hard boundary, a membrane with the right stiffness could be used to simulate the infinite boundary condition but its selection is difficult (Gui, 1995).

5 DISCUSSION

5.1 *Geometry Effect*

It is clear that there are two phases of behaviour depending on the depth ratio Z. Shallower than some critical ratio (Z=10 in Fig 2) 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 the characteristic of deep foundations.

The boundary fringe, ten cone diameters wide, 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 $B/d_{50}>20$.

5.2 *Stress Level Effect*

It has been seen from Fig 11 that the bigger the initial stress level, the smaller the normalised tip resistance Q. Therefore, it is essential to get the correct prototype stress level when modelling the behaviour of the piles or cone penetrometers. It has been possible, using centrifuge data, to discriminate properly between size effects and stress level effects.

6 CONCLUSIONS

The repeatability and the reliability of CPTs in the centrifuge have been found to be very encouraging. Guidelines and standardisation of probes and procedures are proposed for avoiding any spurious effects and allowing comparisons between centrifuge CPT tests carried out in different laboratories.

7 ACKNOWLEDGEMENT

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