INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Horizontal cone penetration testing in sand

Essai de sondage horizontal dans les sables

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ABSTRACT: The cone resistance and sleeve friction measured when a penetration test is executed in a horizontal direction differ from those obtained when sounding in the traditional vertical direction. In a 2m diameter calibration chamber several test series have been executed in differently graded sands and at different densities. These tests show that the ratio of horizontal over vertical cone resistance depends on the density of the sand and less on the gradation. The ratio of sleeve frictions on the other hand depends strongly on the gradation and not so much on the density. These differences will lead to small changes in soil classification charts.

RÉSUMÉ: La résistance à la pénétration et le frottement latéral, mesuré quand un essai de sondage aurait exécuté dans un direction horizontal, différent de ces mesuré à la verticale. Un nombre des essais a exécuté dans un chambre de calibration sur sables avec des courbes de distribution granulométrique différentes et des densités différentes. Ces essais démontrent que le ratio de la résistance à la pénétration horizontal divisé par cette mesuré vertical dépend de la densité, mais pas de la distribution granulométrique. Le ratio du frottements latéral toutefois dépend de la distribution granulométrique et moins de la densité. Ces différences amènera des changements limités aux diagrammes de la classification des sols.

1 INTRODUCTION

The cone penetration test (CPT) has been used extensively over the last decades to measure in situ soil properties. Measurements are traditionally taken from ground level in a vertical downward direction, to gain information about stratification and soil properties. In recent years there has been a growing number of underground construction works, such as tunnel boring projects, for which a soil investigation is needed over large distances as well as to great depths. The typical interval between borings or CPTs from the ground surface for such a project lies somewhere in the range of 50 to 100m, but this may not always be sufficient. In the case of a bored tunnel, the soil investigation can be complemented by cone penetration tests originating from the tunnel boring machine in a horizontal forward direction, as proposed by e.g. van Deen et al. (1999). Although it would not be possible to change the alignment of the tunnel based on this information, the test results could be used to finetune the boring process and improve control of the face support or reduce the settlements caused by the tunnel boring machine.

Although the equipment used to perform a vertical CPT is easily converted for use in a horizontal cone penetration test (HCPT), the interpretation of the test results is not so easily converted. The interpretation of CPTs is normally made using analytical and empirical models, which all implicitely or explicitely assume that the penetration direction is vertical, or that the stress component perpendicular to the penetration direction is radially uniform. In vertical CPTs this is the effective horizontal stress σ'_h after all, and Houlsby & Hitchman (1988) have shown that this stress component governs the cone resistance in calibration chamber tests in sand.

In the case of HCPT however the stress state perpendicular to the cone is not radially uniform, as it varies between σ'_h and the effective vertical stress σ'_v. Combined with the fact that most soils have been deposited in a layerwise manner, it is to be expected that the measurements obtained with HCPT differ from those in vertical CPT.

Such differences have been observed in calibration chamber tests as well as field tests. Field measurements, reported by van Deen et al. (1999), show that the horizontal cone resistance is greater than the vertical, up to three times greater in clay. Other tests, in sand and peat layers, show a similar although less extreme behaviour. Van Deen's observation in a sand layer has a horizontal over vertical cone resistance ratio $q_c^{H/V} = 1.8$.

A number of calibration chamber tests on sands has been executed by Broere & van Tol (1998) on a uniformly distributed sand. These tests showed a horizontal cone resistance q_c^H greater than the vertical cone resistance q_c^V at the same depth. The horizontal cone resistance was on average 1.2 times the vertical for medium dense sand and close to one for very loose or dense sands. Extreme $q_c^{H/V}$ ratios of 0.9 and 1.6 were observed however. The horizontal sleeve friction was clearly lower than the vertical sleeve friction, with f_s^H approximately $0.8 f_s^V$, but showed little dependancy on the density of the sand.

These tests give no indication however of the influence of the grain size distribution of the sand on the horizontal cone resistance or sleeve friction, although the difference between field observation and calibration chamber tests indicates that there may be an influence. To test that hypothesis a number of calibration chamber tests has been performed on differently graded sands.

2 CALIBRATION CHAMBER TESTS

2.1 *The DUT Calibration Chamber*

The calibration chamber at Delft University of Technology (DUT) is a 2m diameter rigid wall calibration chamber, as sketched in figure 1. This chamber differs in a number of ways from the calibration chamber types most often used, as described by Parkin (1988).

Most notable is the fact that the DUT chamber is a rigid wall chamber, meaning that the lateral boundaries are inflexible and prevent horizontal deformation at this point. In normal operation the upper boundary remains free and unloaded and the lower boundary is formed by a stiff perforated steel plate.

On top of this plate a fluidisation system is installed, consisting of filter drains connected to a pump and several water reservoirs. This fluidisation system can be used to fluidise the sand bed in the tank. A couple of vibrators affixed to the sides of the tank can then be used to densify the sand bed. After fluidisation and densification the water can be drained if so desired, allowing tests on saturated or unsaturated sand samples. All calibration chamber tests described in this article have been made in unsaturated samples.

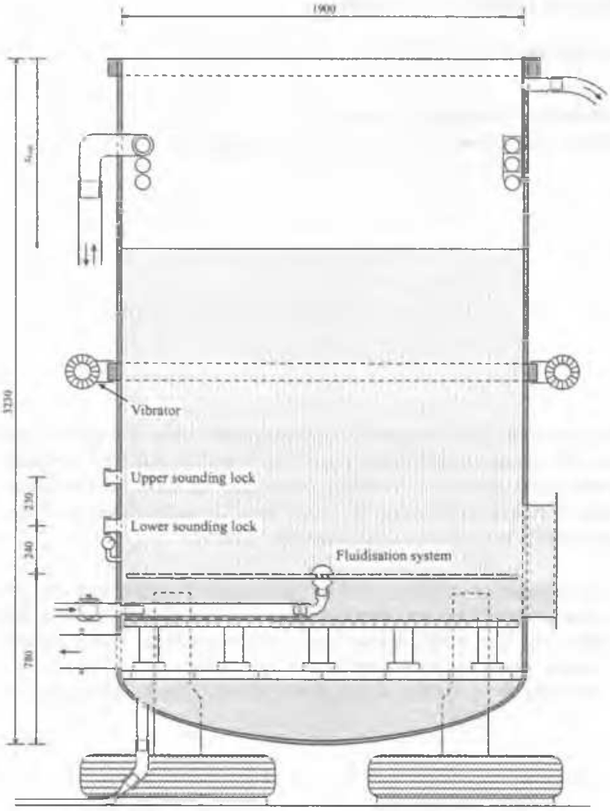

Figure 1. DUT calibration chamber

The main advantage of the fluidisation method, over the commonly used pluviation method, is the relative ease with which a sample can be prepared. As there is no need to completely excavate the chamber each time, a saturated sample can be prepared within an hour, as opposed to the days required for a pluviated sample. The main disadvantage is that the sample obtained in this way is less uniform, as segregation or slight density differences may occur. Without undisturbed sampling these density differences cannot be detected and only the overall density of the sand can be measured. Also, due to the repeated fluidisation of the sand, part of the fines may be washed out over time, slightly changing the grain size distribution.

A further special feature of the tank is of course the presence of two locks in the side of the wall, as sketched in figure 1. These locks are specially designed to allow a horizontal penetration to be made using a standard 35mm cone.

2.2 *The Sands*

In the different test series four different sands have been used. The first two sands are rather similar, both a uniformly distributed fine sand of alluvial origin. The difference between the two lies in the fact that the first sand had been used in the chamber over an extended period of time and that as a result most fines had been washed out. The second sand was taken from a fresh batch and as a result contained a small percentage of fines. The third and fourth sands were obtained by mixing this alluvial sand in different proportions with a commercially available coarse river sand, which had been washed to remove part of the original fines. The four sands are characterised by their sieve curves in figure 2.

For these sands the minimal and maximal densities have been

Table 1. Minimal and maximal densities

Sand	e_{min}	e_{max}
1	0.470	0.818
2	0.498	0.801
3	0.454	0.749
4	0.431	0.746

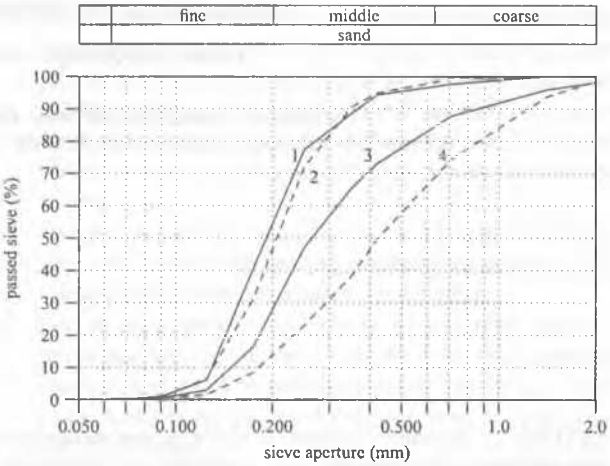

Figure 2. Sieve curves for all sands

obtained by pouring dry sand through a funnel respectively vibrating and compacting a moist sample for an extended period of time. The resulting e_{min} and e_{max} are listed in table 1.

As said before some segregation may occur due to the fluidisation process, as finer particles tend to float upwards. This has been checked by taking samples of the densified sand bed at different depths. Especially for the artificially mixed non-uniform sands 3 & 4 some segragation has been observed in the uppermost 20 cm. Below this layer the sand shows no discernible segregation and the sieve curves shown in figure 2 are obtained from samples taken from this lower region. Sands 1 & 2 are very uniformly graded and as a result show no segregation at all. The effect of the segregation is a slightly larger error in the determination of the relative density of the sand at the depth of the horizontal sounding. This error is however mainly attributed to density fluctuations caused by the densification process. As the overall error margin remains below 5% in all cases, segregation and density fluctuations are not considered major problems for these tests.

2.3 *Overview of Test Series*

All tests have been made using standard 10cm^2 electrical cones equipped with friction sleeves. In each test a sand bed was prepared by fluidisation and densification and a single horizontal CPT was made using either the upper or lower lock position. In the same sand bed also up to three vertical tests were executed, as sketched in figure 3. The resulting (vertical) cone resistance and sleeve friction at the depth of the horizontal test were then compared to the results of the horizontal test.

All in all 69 horizontal and 151 vertical CPTs have been executed in the different sands. The number of horizontal and vertical CPTs differs as in some cases two or only a single vertical test has been made in the same sample. In the first sand 29 ho-

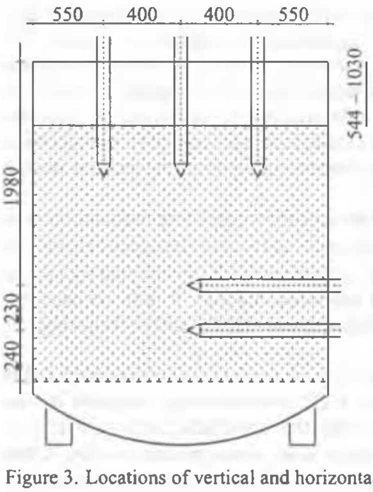

Figure 3. Locations of vertical and horizontal CPTs

rizontal tests have been made using the lower lock position and 10 using the upper lock position. In all but 13 cases three vertical CPTs were made in each sample. In those 13 cases only a single vertical CPT was made for each HCPT. In the other 3 sands 10 horizontal tests were made, accompagnied by two vertical tests in each sample.

For each of the sands the vibration time was varied to obtain different overall densities of the sand bed, resulting in relative densities $10\% < D_r < 80\%$.

3 RESULTS

The horizontal cone resistance q_c^H has been compared to the vertical cone resistance q_c^V measured at the same depth and in the same sample in figure 4. Similarly the horizontal sleeve friction has been plotted against vertical sleeve friction in figure 5. The results have been normalised by the vertical effective stress σ_v', even though the results from calibration chamber tests by Houlsby & Hitchmann (1988) indicate that a normalisation by horizontal effective stress is more useful. Also a similar normalisation is suggested by Wroth (1984), but he also indicates that such a normalisation may be impractical as in many cases the horizontal effective stress is not precisely known. This is the case in a rigid wall calibration chamber such as used in these tests, and as a result a normalisation by vertical effective stress is choosen.

3.1 *Horizontal Cone Resistance*

It can be gained from figure 4 that the horizontal cone resistance is on average larger than the vertical cone resistance. This can also be seen in figure 6, where the ratio of horizontal cone resistance over vertical cone resistance $q_c^{H/V}$ has been plotted against relative density.

For medium dense sands the average ratio $q_c^{H/V}$ is approximately 1.2. For loose and very dense sands this ratio tends towards 1. This indicates that not only the different stress state around the cone influences the horizontal cone resistance, but that it is also affected by the density of the sand.

If on the other hand the results from the four sands are compared to each other, there is no significant difference between those, indicating that the grain size distribution does not influence horizontal cone resistance, at least not differently than vertical cone resistance.

That for normally consolidated sands the horizontal cone resistance is expected to be somewhat larger than the vertical has been explained by Broere (2001) using an elastic cavity expansion model. Based on this simple model a cone resistance ratio

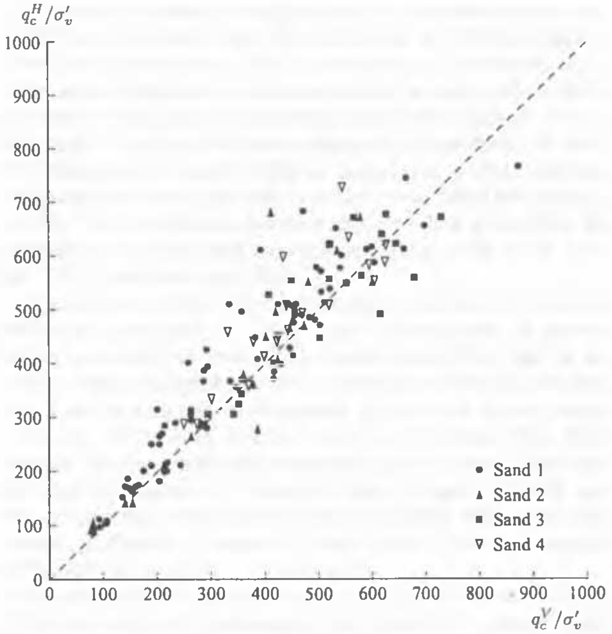

Figure 4. Horizontal vs. vertical cone resistance

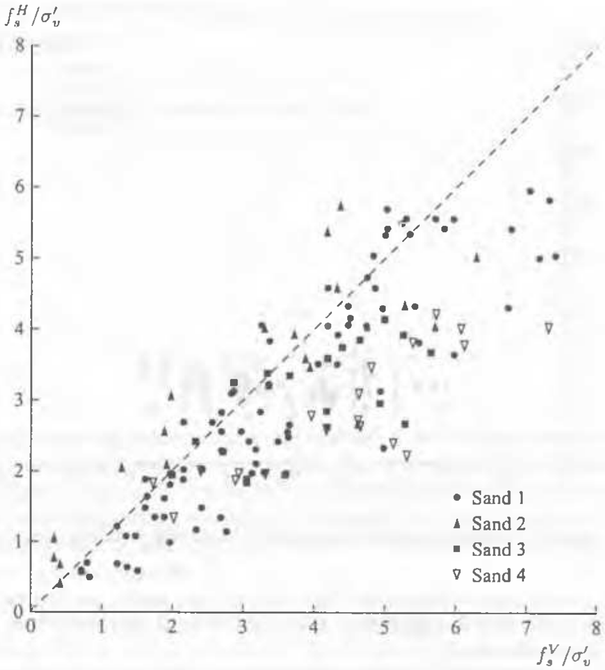

Figure 5. Horizontal vs. vertical sleeve friction

$$q_c^{H/V} \propto \frac{1+K}{K} \tag{1}$$

with K the horizontal stress coefficient, is calculated, i.e. $q_c^{H/V} \approx 1.5$ for normally consolidated sands. This is somewhat larger than the observed ratio, as might be expected from a completely elastic model.

The observed ratio $q_c^{H/V} \approx 1$ at low densities can be understood if it is supposed that at low densities the stress level has little or no influence on the cone resistance, as evident from Schmertmann (1975), so that also differences in the stress state have little influence on the cone resistance.

3.2 *Horizontal Sleeve Friction and Friction Ratio*

In contrast to the cone resistance, the horizontal sleeve friction does show a clear influence of the sand type used. This can be seen in the plot of horizontal vs. vertical sleeve friction (figure 5)

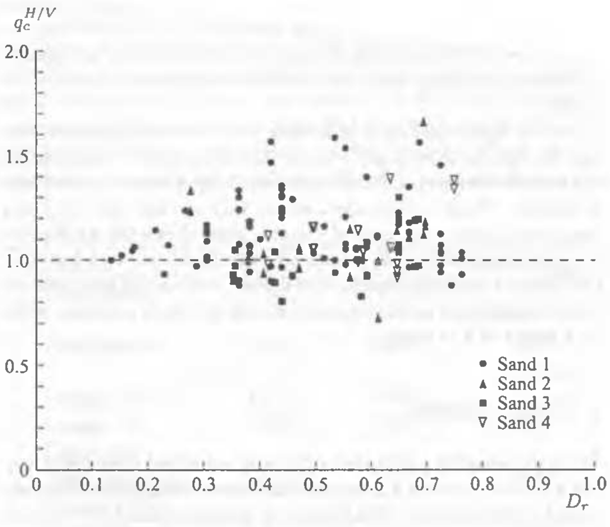

Figure 6. Ratio of horizontal over vertical cone resistance vs. relative density

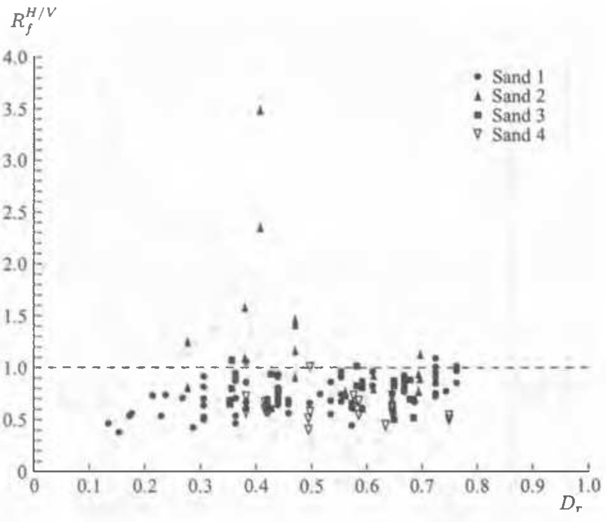

Figure 7. Ratio of horizontal over vertical friction ratio vs. relative density

or even more pronounced if the ratio of horizontal over vertical friction ratios is considered. See figure 7 for a plot of $R_f^{H/V}$ vs. relative density.

The mean $R_f^{H/V}$ is 0.72 for sand 1 and 1.20, 0.77 and 0.60 for sand 2, 3 and 4 respectively. On the other hand there is little or no influence of the density of the sand. The high value of $R_f^{H/V}$ for sand 2 is partly due to the two extreme values (2.4 & 3.5), but all other measurements for this sand also yield relatively large ratios of friction ratio. If those two values are discarded the mean $R_f^{H/V}$ for sand 2 drops to 1.01, but even in that case the differences between the different sand types cannot be attributed to statistical fluctuations only.

It is no more than expected that the friction ratio increases with an increasing fraction of fines and decreases if a larger coarse sand fraction is present. Given the available data it seems however that the horizontal sleeve friction reacts stronger to such changes in grain size distribution than does the vertical sleeve friction, whilst at the same time the average horizontal friction ratio is lower than its vertical counterpart. Although such a combination of effects would explain the observed ratios, the underlying physics are not completely clear.

4 IMPACT ON SOIL CLASSIFICATION CHARTS

Several soil classification charts based on corrected cone resistance q_t and friction ratio R_f have been presented in literature. See e.g. Lunne et al. (1998) for an overview of the most common charts. Given the differences noted above between vertical CPT and HCPT in sand, and the field test results given by van Deen (1999), it is clear that some slight modifications are needed to those charts if they are to be used for the interpretation of HCPT results.

As the horizontal cone resistance is on average slightly higher and the friction ratio slightly lower than their vertical conterparts, the bounds between different soil types shift slightly upward and to the left. There is however a severe lack of data from silt, clay and peats, so that no reliable classification charts for HCPT can be constructed as yet. If a detailed soil classification is based on HCPTs and existing classifcation charts, one should take care, as the horizontal and vertical measurements in clay or peat may differ by a factor of 2 or more.

5 CONCLUSIONS

The cone resistance and sleeve friction measured when performing a CPT in sand in a horizontal direction differ from those obtained in vertical tests. The horizontal cone resistance for medium dense sands is on average 20% higher than the vertical cone resistance. For low densities the horizontal and vertical cone resistance are almost equal. This ratio apparently does not depends on the grain size distribution of the sand.

The horizontal sleeve friction on the other hand is in most cases lower than the vertical sleeve friction, but the ratio depends on the grain size distribution of the sand. For coarse sands with hardly any fines the horizontal friction ratio is apprximately 60% of the vertical friction ratio, whereas for fine sands with a low fines content it can be equal or even somewhat larger than the vertical friction ratio.

The observed differences in both horizontal cone resistance and sleeve friction will lead to shifts in the boundaries between different soil types in a soil classification chart based on HCPT, as compared to those composed from vertical penetration tests. As there is at present limited HCPT data available no reliable classification chart encompassing all soil types can be drawn yet. When an existing classification chart is used to identify soil based on HCPT data care should be taken with respect to the differences between horizontal and vertical CPT stated above.

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