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# Horizontal cone penetration testing

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ABSTRACT: It has been proposed to use horizontal cone penetration tests from a tunnel boring machine to obtain additional information on the soil in front of the TBM. This article gives an overview of various investigations into the feasibility of such a technique. The execution of the test as well as the interpretation of the measurements are considered. Tests from a medium sized TBM show that horizontal CPTs can be executed in a practical manner, that the measurements can be interpreted and the results used to improve control of the boring process. Tests performed in a calibration chamber show slight differences between CPT measurements taken in a horizontal and a vertical tradition. It has been shown that in medium dense sands the horizontal cone resistance can be 20% larger than the vertical cone resistance. This information can be used to fine-tune the test interpretation.

## 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 falls somewhere in the range of 50 to 100m, but this may not always be sufficient in order to gain a reliable overview of the soil stratification. Especially near river crossings in delta areas, the soil variability can be so large that significant changes in the ground are not detected.

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. Although it would not be possible to change the alignment of the tunnel based on this information, the test results could be used to fine-tune the boring process and improve control of the face support or reduce the settlements caused by the tunnel boring machine.

When studying the feasibility of the horizontal cone penetration test (HCPT), two aspects have to be considered: which changes to the equipment are necessary to perform a HCPT instead of a traditional, vertical CPT, and what differences in the test results may occur due to the change in penetration direction. Both aspects have been investigated in several COB (Centrum voor Ondergronds Bouwen) research projects, in cooperation with GeoDelft and Delft University of Technology.

## 2 FIELD TESTS

In a first investigation three horizontal CPTs were performed from a deep excavation in Amsterdam by van Staveren (1997). The HCPTs were made through openings in the sheet pile wall surrounding the excavation. These were compared with two vertical CPTs made just outside the wall as well as a single slanted CPT, that was made at a downward angle (approx. 8 °). The soil consisted of Holocene clay, peat and sand layers. The CPT rig was a standard 100 kN rig without special modifications. It was positioned next to the wall using a freight lift.

Figure 1 shows the results from one of the vertical CPTs on the left and of the slanted CPT on the right. The depth where the slanted CPT was made is indicated in the vertical CPT graph by a thick line. It can be seen that the slanted CPT shows cone resistances slightly larger, but of the same order of magnitude, as those measured by the vertical CPT. Of course the readings are also stretched out, as the penetration is made at an angle of about 8°. These tests show that the horizontal cone resistance is generally larger than the vertical cone resistance, on average 1.5 to 2 times higher, with extreme values up to three times as high in the clay layers. In the sand layer a horizontal over vertical cone resistance ratio $q_c^{H/V}$ of 1.8 was observed.

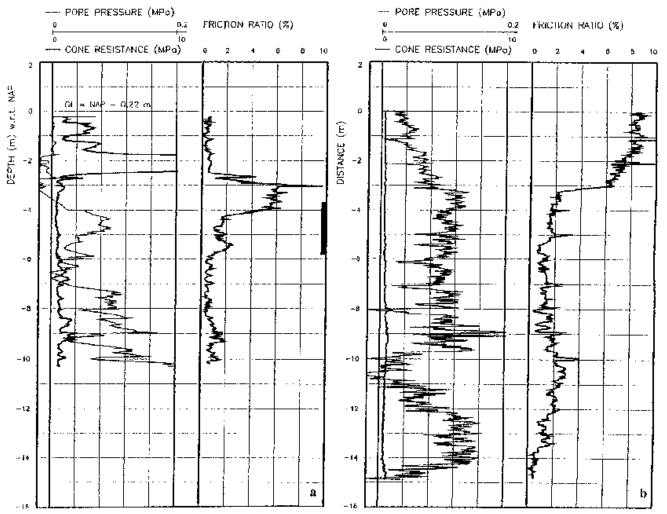

Figure 1. Vertical (left) and slanted (right) CPT results.

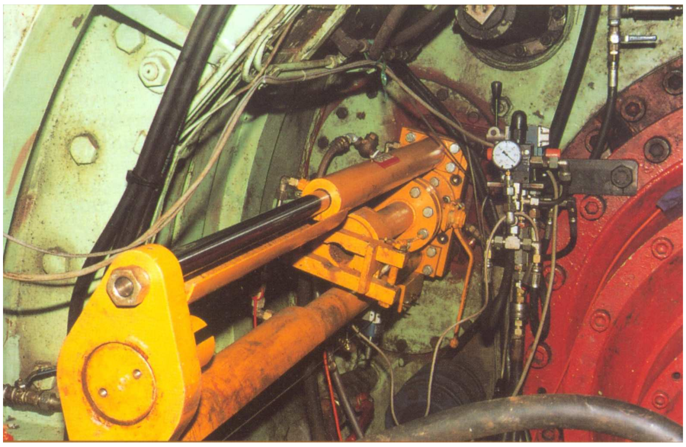

Figure 2. HCPT rig installed in a pipe jacking TBM.

For a second set of tests a specially designed HCPT rig was installed in a pipe jacking machine, used to construct a 3m outer diameter tunnel in Antwerp, Belgium. The CPT rig was slightly altered to better fit in the TBM and a set of water tight locks was installed in the TBM to allow the CPT cone to pass through the bulkhead without groundwater leaking into the machine (van Deen et al., 1999). Figure 2 gives an overview of the rig installed in the TBM.

In total ten HCPTs have been performed from this TBM during standstill of the machine, at depths of approximately 15 metres. One example of the resulting measurements is shown in Figure 3. The cone resistance shows a small peak at the start, when the rods pass through the water tight locks. After that the readings are zero, until the cone passes the cutter wheel and enters the undisturbed fine sand in front of the TBM. From then on it registers a more or less stationary cone resistance, until at 7.5 m from the start, it encounters a clay filled former borehole, which is clearly visible from the readings. After the borehole readings return to a value indicative for the sand. They compare well with the limited amount of data available form vertical CPTs in the area.

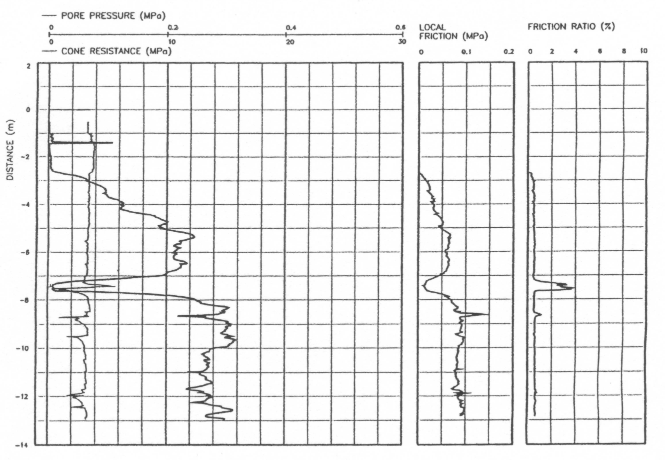

Figure 3. HCPT results in front of TBM.

## 3 CALIBRATION CHAMBER TESTS

### 3.1 *Introduction*

Although the equipment used to perform a vertical CPT is relatively 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 implicitly or explicitly 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 $\sigma_h'$ 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 $\sigma_h'$ and the effective vertical stress $\sigma_v'$. 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 were indeed observed in the field tests. In order to investigate these differences under controlled conditions, a number of calibration chamber tests has been performed on differently graded sands at various densities.

### 3.2 *The TU Delft Calibration Chamber*

The calibration chamber at Delft University of Technology (TU Delft) is a 2m diameter rigid wall calibration chamber, as sketched in figure 4. 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 TU Delft 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.

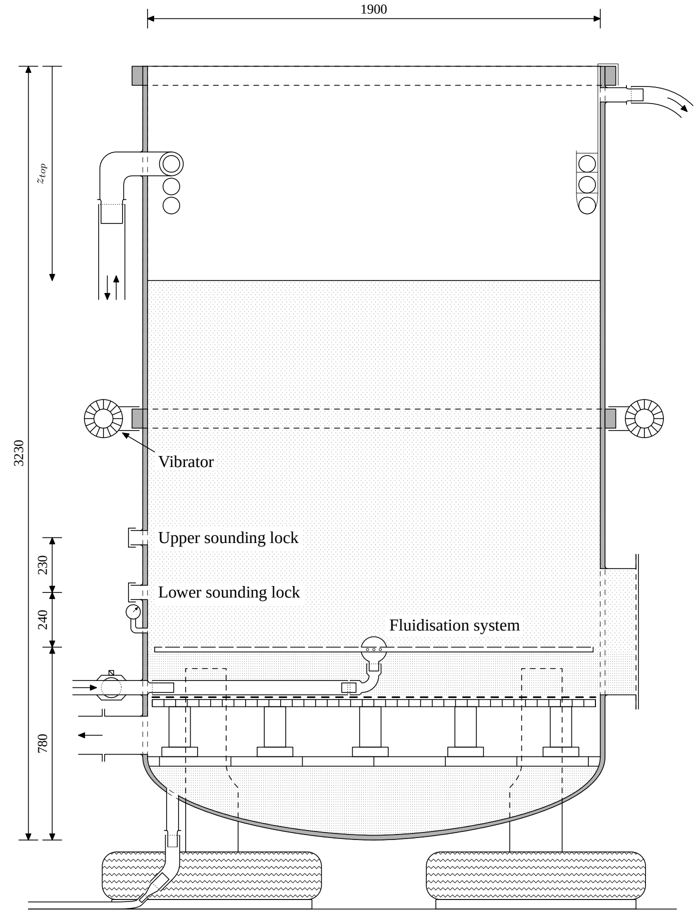

Figure 4. TU Delft calibration chamber

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.

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 4. These locks are specially designed to allow a horizontal penetration to be made using a standard 35mm cone.

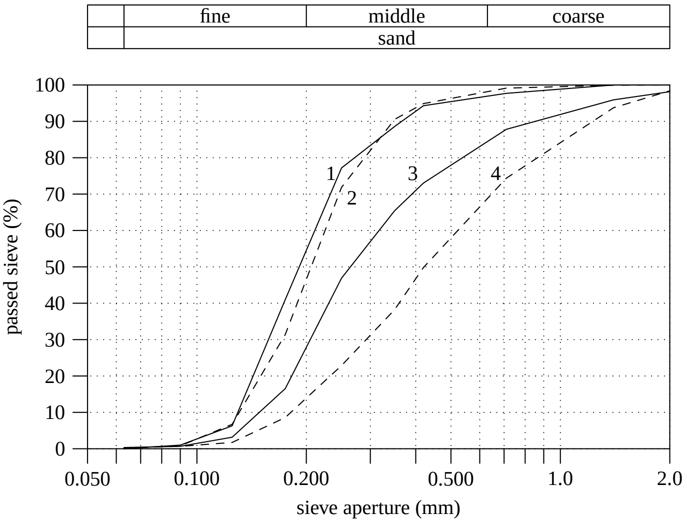

Figure 5. Sieve curves for all sands

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 |

### 3.3 *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 5.

For these sands the minimal and maximal densities have been 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 segregation has been observed in the uppermost 20 cm. Below this layer the sand shows no discernible segregation and the sieve curves shown in figure 5 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

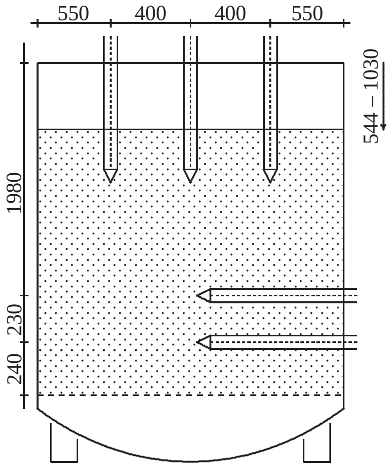

Figure 6. Locations of vertical and horizontal CPTs

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.

### 3.4 *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 6. 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 horizontal 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, accompanied 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 $10\% < D_r < 80\%$.

## 4 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 7. Similarly the horizontal sleeve friction has been plotted against vertical sleeve friction in figure 8. The results have been normalised by the vertical effective stress $\sigma_v'$, 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 chosen.

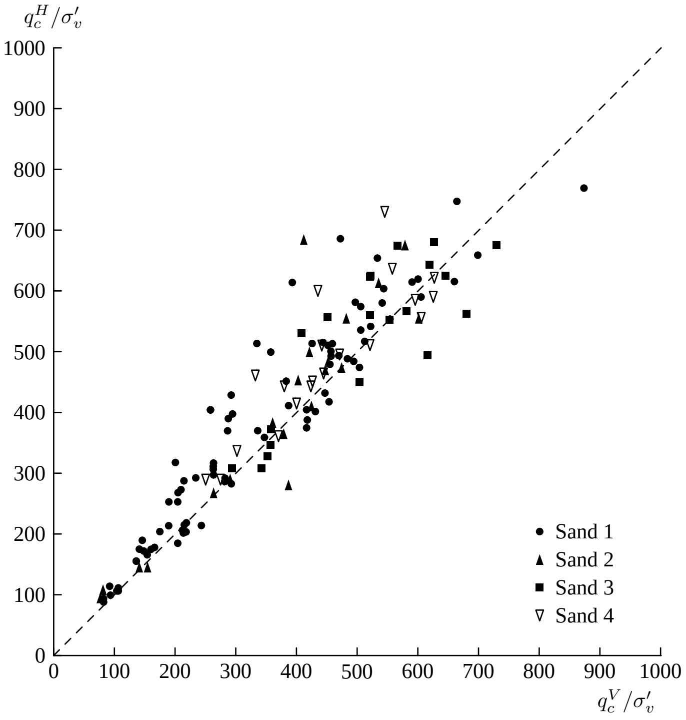

Figure 7. Horizontal vs. vertical cone resistance

### 4.1 *Horizontal Cone Resistance*

It can be gained from figure 7 that the horizontal cone resistance is on average larger than the vertical cone resistance. This can also be seen in figure 9, 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

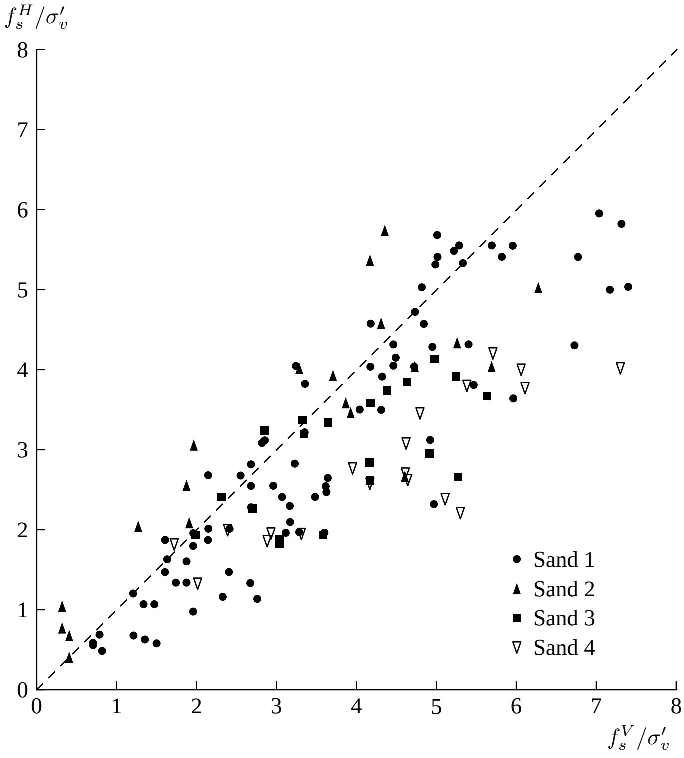

Figure 8. Horizontal vs. vertical sleeve friction

the vertical has been explained by Broere (2001) using an elastic cavity expansion model. Based on this simple model a cone resistance ratio

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

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.

### 4.2 *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 8) or even more pronounced if the ratio of horizontal over vertical friction ratios is considered. See figure 10 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.

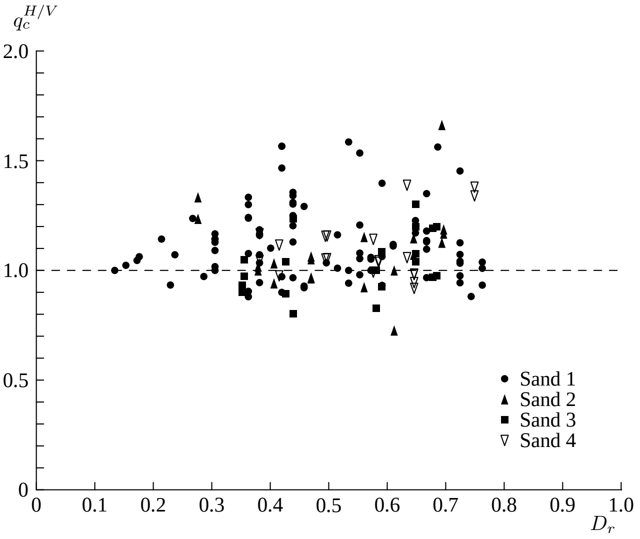

Figure 9. Ratio of horizontal over vertical cone resistance vs. relative density

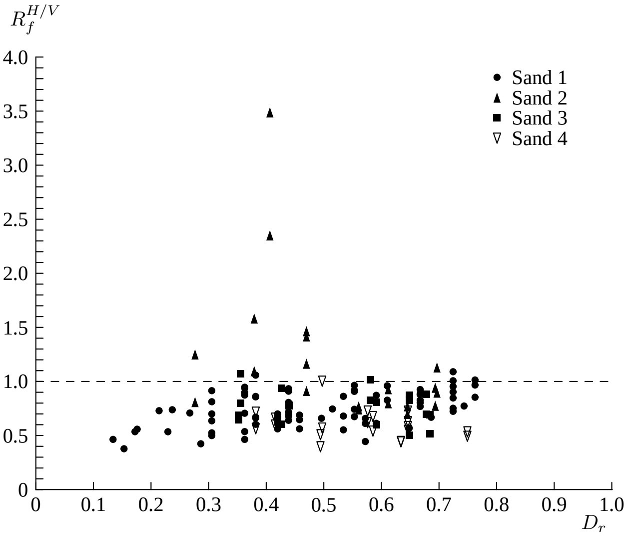

Figure 10. Ratio of horizontal over vertical friction ratio vs. relative density

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.

## 5 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 the calibration chamber, 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 counterparts, 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 classification charts, one should take care, as the horizontal and vertical measurements in clay or peat may differ by a factor of 2 or more.

## 6 CONCLUSIONS

The horizontal cone penetration test is a possible method to investigate the soil conditions in front of a TBM. The information gained can be used to supplement the standard (vertical) soil investigation and fine-tune the boring process. Although the measurements from HCPT and vertical CPT are roughly the same, some differences occur.

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 approximately 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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