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Horizontal Cone Penetration Testing

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ABSTRACT: In order to find the relationship between the cone resistances measured in horizontally and vertically aligned cone penetration tests, a test series has been performed in a 2 m. diameter rigid wall calibration chamber using a 36 mm. cone. This calibration chamber contains an unsaturated uniform sand, which can be prepared at different densities. It is found that the horizontal cone resistance is higher than the vertical cone resistance at a given point, whilst the side friction is lower horizontally than vertically. A simple cavity expansion model is used to explain the ratio of horizontal over vertical cone resistance.

1 INTRODUCTION

The cone penetration test (CPT) has been used extensively over the last decades to measure in situ soil properties, especially in delta areas where the upper layers consist of soft sediments. Measurements are traditionally taken from ground level in the vertical direction, to gain information about stratification and soil properties. With the introduction of mechanized tunnel boring in the Netherlands a need for soil data along the alignment of the tunnel has arisen. As most of these tunnels are built in heavily stratified soils, with strong variation and local irregularities, an extensive soil survey would be needed to gain sufficient information from vertical measurements only. Measurements from ground level are further complicated in urbanized areas where buildings are present over the tunnel alignment. To overcome these problems it has been proposed to perform cone penetration tests from the tunnel boring machine in a horizontal direction. In that way continuous information about the soil directly before the tunnel boring machine can be gained, which can complement the information gained from vertical soil surveys.

Although the equipment used to perform a vertical cone penetration test (VCPT) can easily be converted to allow its use in a horizontal cone penetration test (HCPT), the measurements obtained cannot be interpreted as easily. In a VCPT the horizontal effective stress σ'_h acts around the body of the cone, whilst the vertical effective stress σ'_v acts in the direction of penetration. This stress state around the cone is used implicitely in most theoretical models, e.g. Vesić (1972), Carter (1986), Salgado (1997), and empirical models, e.g. Schmertmann (1975), Houlsby (1988). The initial stress state around the cone in a HCPT differs radically however and is further complicated when one takes into account that most soils have been deposited in a layerwise manner. So it is to be expected that the measurements obtained by a HCPT differ from those obtained in a VCPT.

In order to find the relationship between the measurements from HCPT and VCPT or the relationship between measurements from HCPT and soil properties, a test series has been set up in a calibration chamber in which both a horizontal and a vertical CPT could be performed in the same sand sample. In addition to these tests a simple cavity expansion model is used to explain the differences between horizontal and vertical CPT.

2 TEST SETUP

The test series has been executed in a large diameter rigid wall calibration chamber with a diameter of 1.9 m. and a height of 3 m. In the wall of this chamber two holes have been made, at 2.01 m. and 2.23 m. from the top of the tank. Both openings are sealed with ball valves of 37 mm. internal diameter. This allows a standard 36 mm. cone to penetrate the sand, without sand spilling through the opening along the push rods. A filter bed at the bottom of the tank, in combination with several vibratory units along the tank wall, allows the sand in the tank to be fluidised and compacted, in order to prepare samples at different densities. This results in a sand level between 91 and 103 cm. from the top of the tank, corresponding to relative densities between $R_d = 0.172$ and 0.749. For a schematic layout of the calibration chamber see Figure 1. The sand

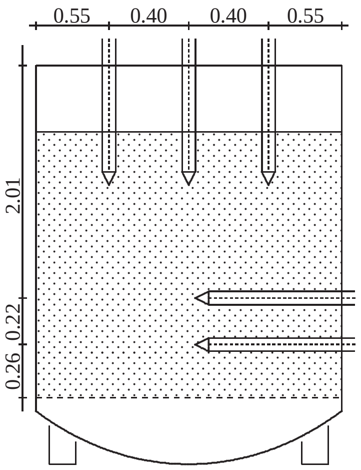

Figure 1. Calibration chamber

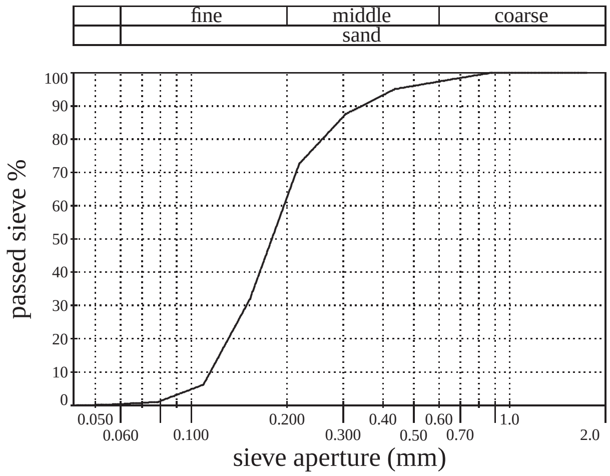

Figure 2. Sieve curve

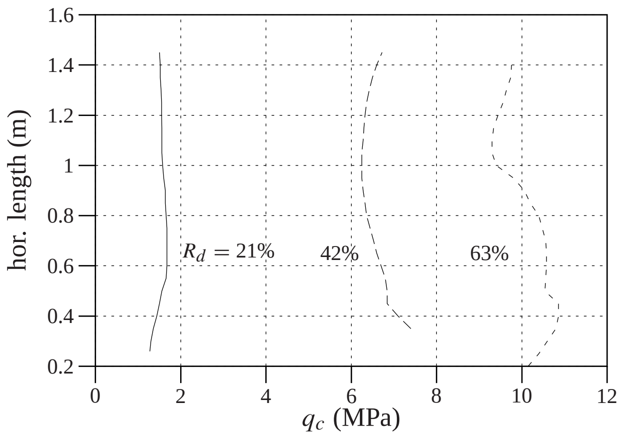

Figure 3. Typical horizontal cone resistance for several densities

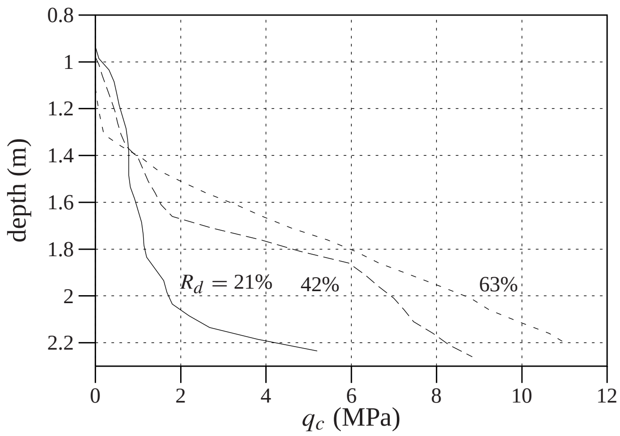

Figure 4. Typical vertical cone resistance for several densities

used in this tank is a uniformely distributed Oosterscheldesand with a $d_{50} = 180\ \mu$, for a detailed distribution see the sieve curve in Figure 2.

Measurements were carried out using a standard 36 mm. cone fitted with a friction sleeve, at the standard speed of 20 mm/s. A push ram was fitted horizontally at one of the wall openings, another could slide over the tank to obtain three vertical measurements in each sample, spaced 0.4 m. from each other and 0.55 m. from the rigid wall in order to minimize the boundary influence for this chamber according to preliminary tests performed in this tank. The vertical penetrations were made in such a way that there was a distance of 5 cm. between the straight path of the horizontal and vertical cones. In this way three points were obtained in each test with both horizontal and vertical cone resistances and side frictions known. A total of 26 samples has been prepared; in ten of those samples the horizontal measurements were obtained at the 2.01 m. level, in the remaining 16 samples the horizontal measurements were taken at the 2.23 m. level.

3 RESULTS

Some typical horizontal cone resistances for different densities at the 2.01 m. level are shown in Figure 3. For each of these densities one of the vertical measurements is shown in Figure 4. It is clear that the HCPT has less variation over its length, as could be expected as the entire penetration takes place at the same stress level, but that the curves show some influence of the rigid boundaries of the tank. The side friction measurements for these penetration tests are not plotted here, but show a common trend with the cone resistance. It should be stated that the horizontal CPTs have been made with different orientation (rotation) of the cone and that this orientation has shown no influence on the measurements.

3.1 *Horizontal cone resistance*

In total 78 combinations of horizontal and vertical cone resistance have been obtained. To combine the results from the tests at the 2.01 m. and 2.23 m. level, all cone resistances have been divided by the effective vertical stress σ'_v. These values have been plotted in Figure 5. The error in the measurements falls within the size of the plot symbol used. The scatter present in the data is accounted to variations in (local) density in the sand.

At first glance there is a lineair relation between the horizontal and vertical cone resistances. When the ra-

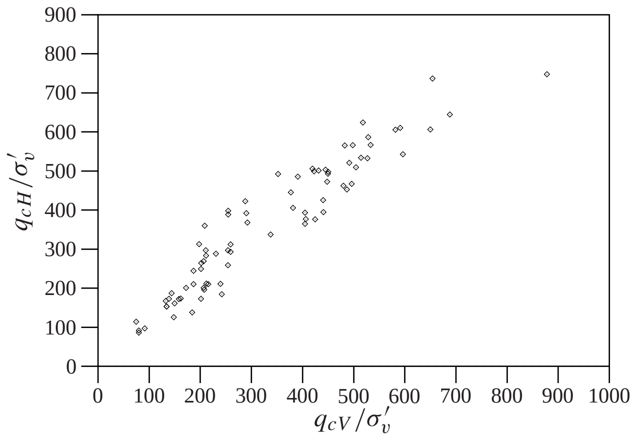

Figure 5. Horizontal vs. vertical cone resistance

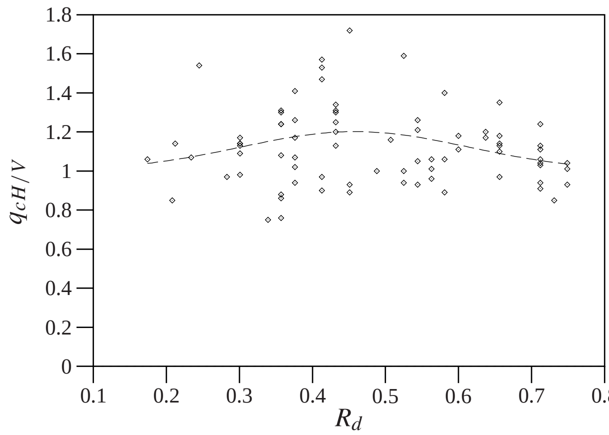

Figure 6. Horizontal over vertical cone resistance vs. relative density

tio of horizontal over vertical cone resistance $q_{cH/V}$ is plotted against the relative density of the sand however (Figure 6), it shows that the relationship between q_{cH} and q_{cV} is not simply lineair. For intermediate densities the mean of horizontal cone resistance is approximately 20% higher than the vertical cone resistance. The authors pose that this is the effect of the differences in the initial stress state of the plane perpendicular to the cone. A more detailed explanation will be given in Section 4.

For low and high relative densities the ratio $q_{cH/V}$ approaches one. This value of $q_{cH/V}$ at these limits can be deduced from simple considerations without going into detail about the influence of the stress state. For low densities Schmertmann (1975) has shown that there is almost no dependence of the cone resistance on the stress level. If this also holds for horizontal CPT, it can be expected that for low densities the cone resistance is only a function of density, and therefore that $q_{cH/V}$ approaches 1. High densities on the other hand are realised in this calibration chamber by prolonged vibrating. This not only densifies the sand, but also increases the effective horizontal stress σ'_h and thereby the value of $K = \sigma'_h/\sigma'_v$. This overconsolidation effect has been measured using an earth pressure gauge. These measurements show that for relative densities between 0.6 and 0.8 the value of K increases from 0.5 to 1. Therefore at high densities, where $K = 1$, there is no difference between the stress states around the horizontal and vertical cone. In that case we expect the cone resistance to be independent of orientation, and therefore the $q_{cH/V} = 1$.

Given the scatter in the data, no function adequately describes the relation between $q_{cH/V}$ vs. R_d. The mean of these measurements however can be described by the function

$$q_{cH/V} = 1 + 0.20e^{-20(R_d-0.46)^2} \qquad (1)$$

which expression has been plotted as the dashed line in Figure 6.

3.2 *Horizontal side friction*

As the cone used had been fitted with a friction sleeve the side friction has been obtained along with the cone resistance. For all measurements the side friction has been divided by the cone resistance to obtain the friction number R_f. This friction number is frequently used to get an indication of soil stratification from a CPT. As Begemann (1969) has shown there is a relation between the amount of fines and the friction number, where a friction number around 1% indicates clean sand. In that light it is of interest whether the horizontal friction number R_{fH} is equal to the vertical friction number R_{fV}, and the established relation between friction number and soil classification also holds for horizontal CPT.

The obtained horizontal friction number has been plotted against the vertical friction number in Figure 7. It can be seen that the horizontal and vertical friction number show the same amount of scatter and that the vertical friction number is equally distributed around 1.06% . It is also clear that the horizontal friction number is lower than would be expected. This effect becomes even more apparent when the ratio of horizontal over vertical fricion number $R_{fH/V}$ is plotted in Figure 8 against relative density. The mean of all the horizontal over vertical friction numbers plotted here lies at $R_{fH/V} = 0.76$. There is no clear dependency of this ratio on the density, nor on the ratio of cone resistances. If the effect of lower horizontal side friction occurs in other soils too, the classification charts based on friction numbers will probably have to be recalibrated for HCPT.

4 CAVITY EXPANSION MODEL

One of the methods to describe a vertical cone penetration is by use of a cavity expansion model, as proposed by Vesić (1972) and adapted by numerous authors. Measurements by Houlsby and Hitchman (1988) have shown that the effective horizontal stress σ'_h is of con-

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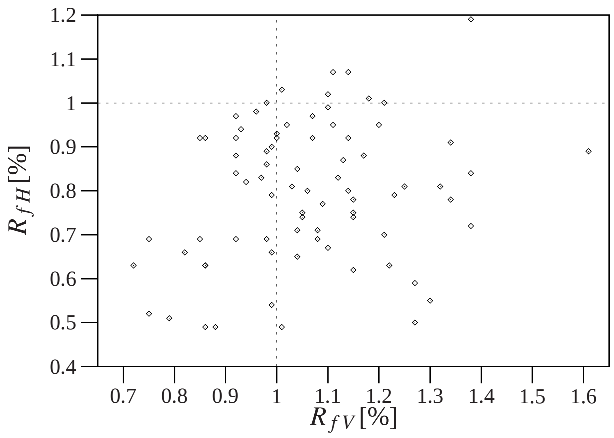

Figure 7. Horizontal vs. vertical friction number

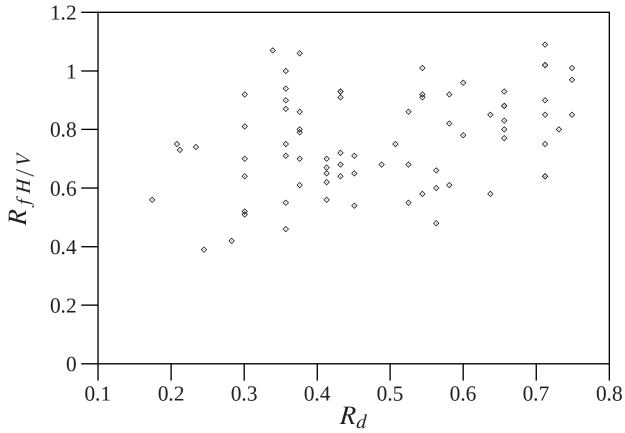

Figure 8. Horizontal over vertical friction number vs. relative density

trolling influence on q_c. This correlation between σ'_h and q_c leads a.o. Salgado et al. (1997) to propose a cilindrical cavity expansion as the basis for a model of cone penetration. Using the assumption that plane strain conditions hold for this problem, the cavity expansion can entirely be described as the expansion of a circular cavity in a plane perpendicular to the penetration direction. For a vertical CPT the initial stress state in this plane is a uniform radial stress equal to σ'_h, as sketched in Figure 9. Although such a model cannot describe the deformations in front of and around the cone in full detail, it shows the correct correlation between σ'_h and q_c.

To describe a horizontal CPT using a similar model we again propose a circular cavity in a plane perpendicular to the penetration direction. The difference lies in the more complicated stress state in this plane. The initial stress varies between σ'_h and the generally higher σ'_v, see Figure 9. This non-uniform stress state somewhat complicates the model.

The initial stress state in the vertical case is simply given by

$$\sigma_{rrV} = -\sigma'_h, \tag{2}$$

while the horizontal stress state, dependant on the

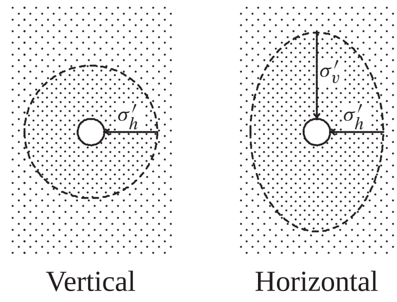

Figure 9. Stress state around cone for vertical and horizontal CPT

angle θ with the vertical, can be approximated by

$$\sigma_{rrH} = -\frac{\sigma'_v + \sigma'_h}{2} - \frac{\sigma'_v - \sigma'_h}{2}\cos 2\theta, \tag{3}$$

where in both cases σ_{rr} is the radial stress component. Combining these stress states with a uniform radial displacement at the cavity boundary, the expansion in a hyperelastic medium can be solved straightforward using the general solution method described by Muskhelishvili (1954). In this way we obtain the stress and deformation states around the cavity. These cannot be compared directly with each other, due to the angle dependency of the horizontal solution and as such give little information on the relation between horizontal and vertical CPT. For both cases however we can calculate the total work done in expanding the cavity, integrated over all angles θ. The work W in these cases is defined by

$$W = \int_0^{2\pi}\int_{r'}^{\infty}\int_{\epsilon_0}^{\epsilon_{r'}} \sigma(\epsilon) r \,\mathrm{d}\epsilon \,\mathrm{d}r \,\mathrm{d}\theta \tag{4}$$

with $\sigma(\epsilon)$ the stress state around the cone as function of the strain ϵ, ϵ_0 and $\epsilon_{r'}$ the initial and final strains, and r' the radius of the cavity. The radial strain, equivalent to a displacement from $r = 0$ to $r = r'$ is, within the limits described for this cylindrical analysis, mathematically equivalent to the expansion of the soil around the cone tip, except of course for a factor describing the geometry of the cone tip. Introducing

$$m = \frac{\lambda + \mu}{\mu} \tag{5}$$

where λ and μ are the Lamé constants, the resulting work for the vertical and the horizontal case can be written surprisingly simple as

$$W_V = \frac{2\pi}{m}\sigma'_h r'^2 \tag{6}$$

and

$$W_H = \frac{2\pi}{m}\frac{\sigma'_v + \sigma'_h}{2} r'^2. \tag{7}$$

When we assume the work, calculated in this way for a purely elastic case, differs only a constant factor from

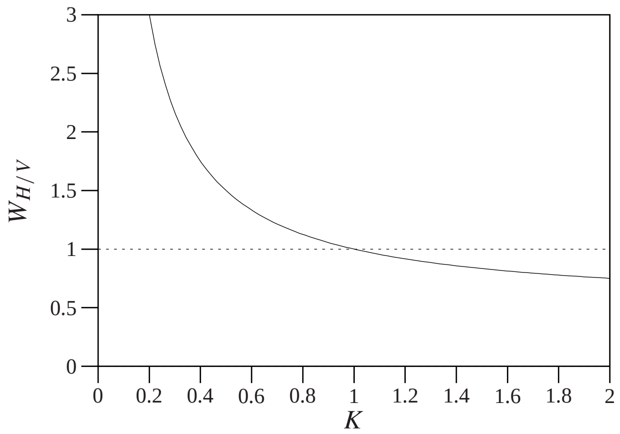

Figure 10. Ratio of horizontal over vertical cone resistance vs. earth pressure coefficent

the work done in pushing the cone a distance into the soil, and when we assume that this factor is the same for both the horizontal and the vertical case, it follows that the ratio of W_H over W_V is equivalent to the ratio of horizontal over vertical cone resistance $q_{cH/V}$, and we can easily calculate this ratio as a function of the earth pressure coefficient K. It follows that

$$q_{cH/V} = \frac{W_H}{W_V} = \frac{1+K}{2K} \tag{8}$$

This function has been plotted in Figure 10.

As would be expected this expression for $q_{cH/V}$ is 1 for $K = 1$. For values of K around 0.5, indicating normally consolidated soils, the ratio is higher than 1, for example $q_{cH/V} = 1.5$ for $K = 0.5$. This is somewhat higher than the ratio $q_{cH/V}$ observed, but this difference can be attributed to the absence of plasticity in the model. For lower values of K this effect is even stronger. For a more exact description of the expansion process plasticity must of course be incorporated into the model. The relatively simple model presented here is only intended to illustrate the underlying mechanism which causes the measured – higher – horizontal cone resistances.

5 CONCLUSIONS

It has been shown that the measurements from horizontal cone penetration testing in sand differ somewhat from those obtained in vertical CPT. For normally consolidated soils at intermediate relative densities the horizontal cone resistance is averagely 20% higher than the vertically measured value. This difference can be attributed to the different initial stress state of the soil in a plane perpendicular to the cone penetration direction. The side friction, expressed as the friction number, is lower when measured in a HCPT than in a VCPT. If this effect occurs in other soils too, the soil classification charts based on friction numbers should be slightly modified for HCPT. To pass a final judgement on this matter a number of tests has to be executed in other types of soil.

Besides the direct use in interpreting the measurements from HCPT, the observed influence of the initial stress state on the cone resistances can be used in order to improve the models used to describe cone penetration testing. Even though it is inconvenient for the interpretation of field tests that the stress state perpendicular to the penetration direction is of major influence on q_c, this effect should be taken into account when interpreting CPT.

6 ACKNOWLEDGEMENTS

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NOTATION

d_{50}	diameter at which 50% passes sieve
K	earth pressure coefficient
m	alternative elastic modulus
r	radial distance from the centre of the cavity
r'	ultimate radius of the cavity, radius of the cone tip
R_d	relative density
R_f	friction number
R_{fH}	friction number from a horizontal measurement
R_{fV}	friction number from a vertical measurement
$R_{fH/V}$	ratio of horizontal over vertical cone resistance
q_c	cone resistance
q_{cH}	cone restistance from a horizontal measurement
q_{cV}	cone restistance from a vertical measurement
$q_{cH/V}$	ratio of horizontal over vertical cone resistance
W	work done in expanding the cavity
W_H	work in case of horizontal CPT
W_V	work in case of vertical CPT
$W_{H/V}$	ratio of horizontal over vertical work
ϵ	strain
ϵ_0	initial strain, eq. to $r = 0$
$\epsilon_{r'}$	final strain, eq. to $r = r'$
λ	first Lamé constant
μ	second Lamé constant
θ	angle with the vertical direction
σ	stress
σ'_h	horizontal effective stress
σ'_v	vertical effective stress
σ_{rr}	radial stress
σ_{rrH}	radial stress in case of horizontal CPT
σ_{rrV}	radial stress in case of vertical CPT