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BEARING CAPACITY OF PILES INFLUENCED BY BUILDING STAGES

CAPACITE PORTANTE DES PIEUX INFLUENCEE PAR LES ETAPES DE CONSTRUCTION

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SYNOPSIS: In the Netherlands it is common practice to design piled foundations using the results of cone penetration tests (CPT´s). These tests are commonly performed prior to the commencement of constructionworks. Effective soil stresses influence the results of these tests. During building stages, especially when pits are excavated or when piles are driven close to each-other, these stresses will change. Excavations will reduce the cone resistance; the densification caused by piling will increase it. In design calculations, the effects of decreasing soil stresses are often over-estimated and the effects of increasing these stresses under-estimated. Better knowledge of these effects results in a optimum and economic pile foundation.

The duplication of the railway tunnel at Schiphol involved the installation of a great number of tension piles. Delft Geotechnics, in co-operation with Ingenieursbureau Nederlandse Spoorwegen (NS) and Nederhorst Grondtechniek (NGT), have performed site investigations during the construction of the tunnel in order to measure the effects of excavations and densification caused by piling.

OBJECTIVE OF STUDY

The investigations, consisting of cone penetration tests, were performed at the location of part T19 (Figure 1), after stages of the construction were completed (Figure 2). The purpose of these investigations was to measure the variations in cone resistance and local friction, from the initial site conditions (stage 1), resulting from the construction stages:
- pile driving, from original ground level (stage 2).
- excavation of soil under water (stage 3).
- pile group loading in tension, after dewatering (stage 4).

DESCRIPTION OF CONSTRUCTION

For the duplication of the railway tunnel at Schiphol, vertical tension piles with a concrete floorslab poured underwater were selected to resist the buoyancy of a tunnel. A plan of the site showing the locations of the cone penetration tests is presented on Figure 1.

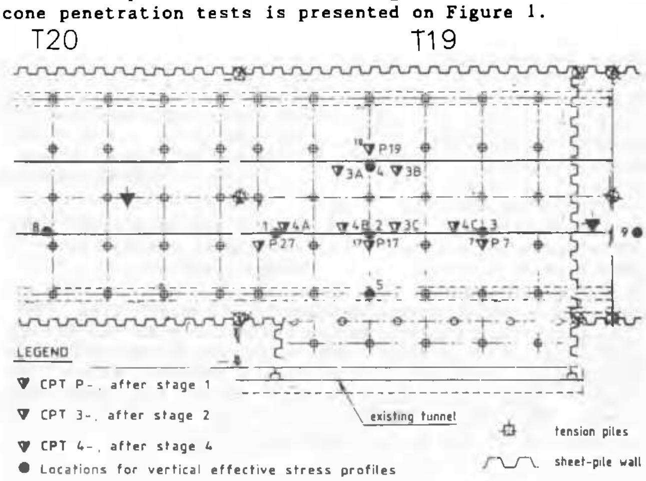

Fig.1. Site plan.

Cross-sections are presented on Figure 2.

Stage 1: Preparation of site: The sheet pile walls are driven to depth and grout anchors installed to stabilise both the existing tunnel elements and the sheet pile walls. Stage 1 soil investigation performed (Cone Penetration Tests P7, P17, P19 and P27; Figure 3).

Stage 2: Driving of Vibro-combinatie piles from ground level: Steel pipe, dimensions 556 mm x 16 mm, with sacrificial steel baseplate. Precast prestressed concrete pile dimension 350 mm square, centred within steel tube. Grout is injected into the space between steel tube and concrete pile, with the steel tube being with-drawn upwards. The Vibro-combinatie piles are installed to a depth of 23 m - NAP (from initial ground surface 4.8 m - NAP) at a grid spacing of 2.65 m x 3.00 m (Figure 1). Stage 2 soil investigation performed (CPT´s 3A, 3B, and 3C).

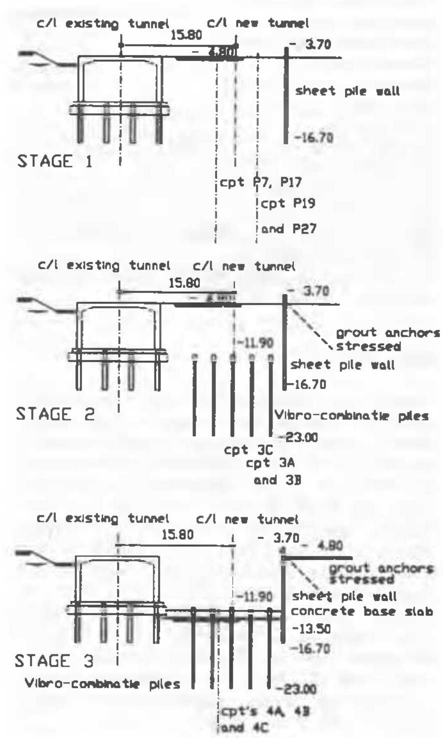

Fig. 2 cross sections stages 1,2 and 4

Stage 3: **Excavation:**
The soil between the sheet pile walls is excavated.

Stage 4: **Pile loading:**
The tunnel floorslab (poured underwater) is completed and the trench pumped dry. At this stage, the piles take up the maximum tensile load.
Stage 4 soil investigation performed (CPT´s 4A, 4B and 4C)

SITE INVESTIGATION

For the purpose of this investigation, a total of 10 CPT´s have been performed after stages in the construction. All cpt´s included measurement of local friction, pore water pressures and inclinometer readings. The locations of the cpt´s are shown on Figure 1. No investigation was performed after the excavation (stage 3). The cpt´s performed after pile loading (stage 4), therefore measure the combined effects of excavation and pile group loading.
The investigation was performed in the middle of the trench and in stages 2 and 4 in the centre of a group of 4 piles. This to minimise the effects of the sheet pile walls (passive earth pressures) and to be on the area where the maximum tension will be applied to the piles.

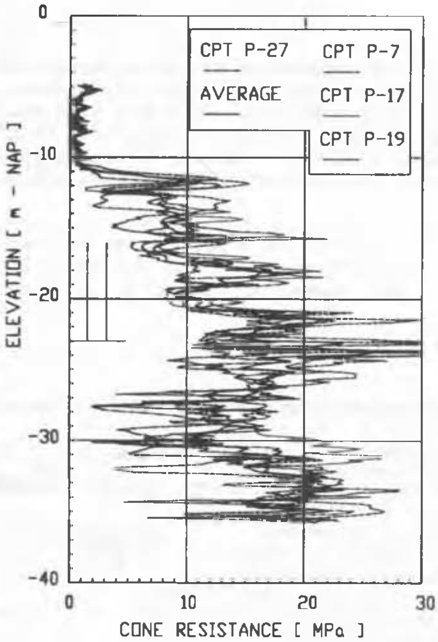

Fig. 3. Summary of CPT results stage 1

SOIL PROFILE

From the results of the investigation the general soil profile can be described as follows:
Very loose silty and clayey sand from the surface to a depth of 10.5 m - NAP with cone resistance of less than 2 MPa. A sand deposit from 10.5 m - NAP to a depth ranging from 24.0 m - NAP to 27.0 m - NAP; cone resistance generally increasing with depth from 2 MPa to 15 MPa with peak cone resistances of greater than 20 MPa. Varying in depth ranging from 24.0 to 27.0 m - NAP to a depth ranging from 29.0 to 32.5 m - NAP, a sand and silty sand layer. The cone resistances vary considerably, ranging from 2 MPa to 18 MPa, over the depth and between cpt´s. Finally a sand layer with cone resistances from 15 MPa to greater than 20 MPa, generally increasing with depth to the final depth of investigation at 36.0 m - NAP.

COMPARISON OF CPT RESULTS

The cone resistance results have been compared between cpt´s that are performed close to each other, refer to Fig. 1, and between the averaged results from all of the cpt´s made in each stage. Cpt´s were executed after the completion of the construction stage, (i.e. cpt´s P-, 3- and 4- refer to investigations performed after stages 1, 2 and 4 respectively).
Comparisons of the averaged cone resistances after the stages 1 and 2, 2 and 4, 1 and 4 are presented graphically on Figure 4, 5 and 6.

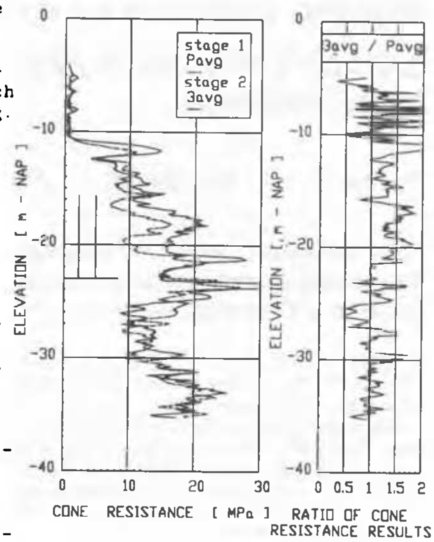

Fig 4. Comparison of average cone resistance results from stage 1 and stage 2

DISCUSSION

As there were no investigations after the excavation of the trench (stage 3), the cpt´s 4A, 4B and 4C measure the combined effects of the excavation and the effect from the pile group loading.
The depth range that effects the ultimate tensile capacity of the piles, is the range from 14.0 m - NAP to 23.0 m - NAP.
From the comparisons shown on the figures the results show that the pile driving (stage 1 to stage 2), produces an increase in cone resistances generally in the range from 20 % to 50 %, Figure 4. The combination of the excavation and pile group loading (stage 2 to stage 4) produces a decrease in cone resistances of generally 40 % to 50 % for the top 3 m and 10 % to 20 % over the lower pile length (Fig. 5).
The comparison of the results below the pile tip level, from 23 m - NAP to 29 m - NAP, show decreases in cone resistances from stage 1 to stage 2 and from stage 2 to stage 4. This depth range is just below the pile tip level. The decrease that occurs may be the result of variability of the soil between cpt results.

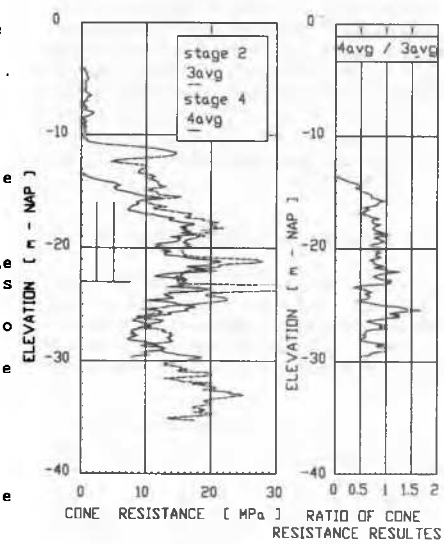

Fig. 5. Comparison of average cone resistance results from stage 2 and 4.

EVALUATION

Typically, a site investigation is performed before the start of construction and the results are used for the design. Prior to construction it may often be necessary to estimate the effects of the construction and building stages on the underlying soil and therefore on the results of the site investigation. In the following several options are evaluated. These options estimate the variation in cone resistance from the variation in vertical effective stress and with assumptions concerning the variation in horizontal effective stress.

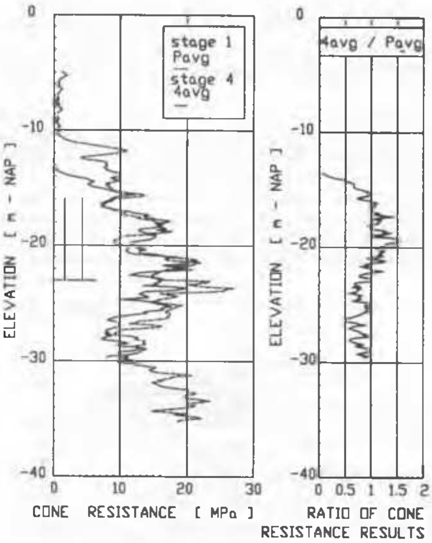

Fig. 6. Comparison of average cone resistance results from stage 1 and stage 4

Vertical Effective Stresses

The situation at the site, at the time when the cpt´s were performed, are presented on Figure 2. Vertical effective soil stresses have been calculated at 9 locations, refer to Figure 2. Only the stresses at location 2 are presented (Figure 7). The calculations are based on the formulae for stress distribution by Boussinesq. The initial ground surface and ground water levels have been assumed at 4.8 m - NAP. For the existing tunnel, it has been assumed that the weight of the tunnel elements is approximately equal to the buoyancy. For the calculation of the vertical effective stresses, this is then equivalent to an excavation to a level of 13.5 m - NAP. The tension loads applied to the piles, after T19 is pumped dry (i.e after stage 4), have been assumed to be equivalent to a uplift of 60 kPa, which includes the weight of the concrete base slab and assumes a groundwater level of 4.8 m - NAP. The pile tension loads are assumed to be resisted by pile shaft friction with a triangular distribution. The shaft friction increases linearly from nil below the pile top (14.5 m - NAP) to a maximum at the base.

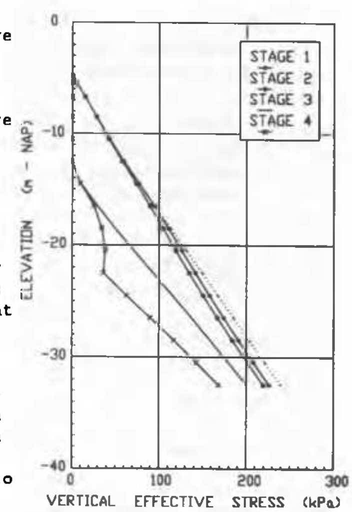

Fig. 7. Vertical effective stress profile at location 2.

Variation of Cone Resistances

From the stress profile at location 2, the expected variation in cone resistances has been calculated, for three options:

<u>Option 1:</u> ratio of cone resistance equal to the ratio of vertical effective stress:

$$\boxed{\frac{q_{cn}}{q_{co}} = \frac{\sigma_{vn}}{\sigma_{vo}}}$$

Options 2 and 3: ratio of cone resistance equal to the ratio of isotropic effective stress.

$$\boxed{\frac{q_{cn}}{q_{co}} = \frac{\sigma_{in}}{\sigma_{io}}}$$

where :

q_{cn}, q_{co} = cone resistance (new),(old)
σ_{vn}, σ_{vo} = vertical soil stress (new),(old)
σ_{in}, σ_{io} = isotropic soil stress (new),(old)
σ_{hn}, σ_{ho} = horizontal soil stress (new),(old)

$$\sigma_h = K \times \sigma_v \quad (1) \quad \text{and} \quad \sigma_i = \frac{1}{3} \times (\sigma_v + 2 \times \sigma_h) \quad (2)$$

Pile Installation (stage 1 / stage 2)

The effect of the pile installation (stage 1 to stage 2) is evaluated as follows,

<u>Option 1</u>:

$$\boxed{\frac{q_{c2}}{q_{c1}} = \frac{\sigma_{v2}}{\sigma_{v1}}} \quad (3)$$

<u>Option 2</u>: assume that the installation of the piles has caused an increase in horizontal stresses in the soil; the K-value increases from K=0.5 (after stage 1), to K=1.0 (after stage 2).

<u>Option 3</u>: assume that the installation of the piles has caused no increase in horizontal stresses in the soil; the K value remains constant; K=0.5 (after stage 1), K=0.5 (after stage 2).

Options 2 and 3 result in the following formulae for the horizontal soil stress,

$$\sigma_{h1} = K_1 \cdot \sigma_{v1} \quad \text{and} \quad \sigma_{h2} = K_2 \cdot \sigma_{v2}$$

$$\frac{q_{c2}}{q_{c1}} = \frac{\sigma_{i2}}{\sigma_{i1}} = \left(\frac{\sigma_{v2} + 2 \cdot K_2 \cdot \sigma_{v2}}{\sigma_{v1} + 2 \cdot K_1 \cdot \sigma_{v1}} \right)$$

$$= \frac{\sigma_{v2}}{\sigma_{v1}} \cdot \left(\frac{1 + 2.K_2}{1 + 2.K_1} \right) \quad (4)$$

where follows:

Option 2A (above pile-tip level) :K_1=0.5, K_2=1.0

$$\boxed{\frac{q_{c2}}{q_{c1}} = \frac{\sigma_{v2}}{\sigma_{v1}} \cdot \frac{3}{2}}$$

Option 2B (below pile-tip level) and option 3:

$K_1 = 0.5, \quad K_2 = 0.5$

$$\boxed{\frac{q_{c2}}{q_{c1}} = \frac{\sigma_{v2}}{\sigma_{v1}}}$$

Note: options 1, 2B and 3 are equivalent.

The predicted variations in cone resistances (i.e. ratio of cone resistances, stage 2 / stage 1) are presented graphically on Figure 8.

Excavation and Pile Loading (stage 2/stage 4)

The effect of the excavation and pile loading (stage 2 to stage 4) is evaluated as follows:

<u>Option 1</u>: similar to (3)

<u>Options 2, 3</u>: assume that the horizontal stresses remain constant (i.e. equal to horizontal stresses after the installation of piles) during the excavation and dewatering (pile loading) stages. During these stages, the vertical soil stresses decrease.

$$\sigma_{h2} = K_2 \cdot \sigma_{v2} \quad \text{and} \quad \sigma_{h4} = K_2 \cdot \sigma_{v2} \quad (!!)$$

$$\frac{q_{c4}}{q_{c2}} = \frac{\sigma_{i4}}{\sigma_{i2}} = \left(\frac{\sigma_{v4} + 2 \, . \, K_2 \cdot \sigma_{v2}}{\sigma_{v2} + 2 \, . \, K_2 \cdot \sigma_{v2}} \right)$$

$$= \left(\frac{\sigma_{v4}}{\sigma_{v2}} + 2.K_2 \right) . \left(\frac{1}{1 + 2.K_2} \right) \qquad (5)$$

Option 2A (< 23 m - NAP) : $K_2 = 1.0$

$$\boxed{\frac{q_{c4}}{q_{c2}} = \left(\frac{\sigma_{v4}}{\sigma_{v2}} + 2 \right) . \frac{1}{3}}$$

option 2B (> 23 m - NAP) and option 3 : $K_2 = 0.5$

$$\boxed{\frac{q_{c4}}{q_{c2}} = \left(\frac{\sigma_{v4}}{\sigma_{v2}} + 1 \right) . \frac{1}{2}}$$

The predicted variations in cone resistances (i.e. ratio of cone resistances, stage 4/stage 2) are presented graphically on Figure 9.

Remarks and Conclusions

stage 1 to stage 2: Pile Installation,

The Vibro-combinatie piles are installed, by driving, to a depth of 23 m - NAP and at a grid spacing of 2.65 m x 3.00 m. From the results from cpt's performed before and after pile installation, an increase in cone resistances of 20 % to 50 % has been measured over the depth of the pile. As shown on Figure 8, the assumption that the K-value has increased from 0.5 to 1.0 (option 2), as a result of pile driving, produces a reasonably good approximation of the increase in cone resistances.

stage 2 and 4: Excavation And Pile Loading

The combined effects of excavation and pile loading have caused a decrease in cone resistance. The decrease, in comparison with the results after pile installation, varied from 40 % to 50 % at the surface to 10 % to 20 % at the pile tip level.

Excavation and pile loading (in tension) reduce the vertical effective stress. As shown on Figure 9, the assumption that the horizontal stresses do not reduce with the vertical stress (options 2 and 3), produce a reasonably good approximation of the decrease in cone resistances. The assumption that horizontal stresses decrease with vertical stresses (equivalent to option 1) produces estimated cone resistances lower than measured.

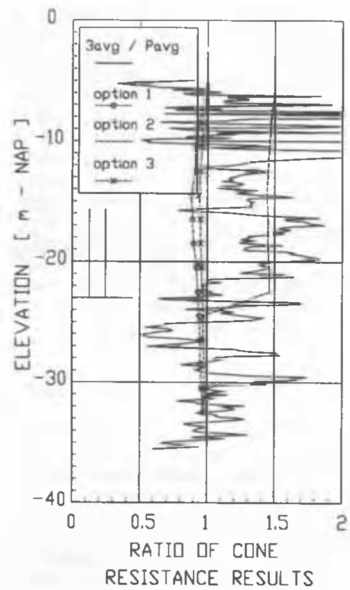

Fig. 8. Ratio of predicted and measured CPT results (stage 2 and stage 1)

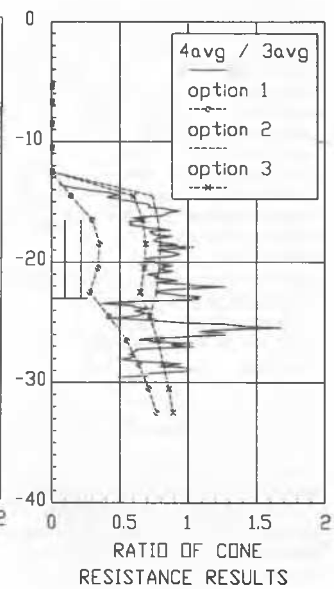

Fig. 9. Ratio of predicted and measured CPT results (stage 4 and stage 2)

For the calculation of the variation in the vertical effective stress (for stage 4), a distribution of shaft friction over the pile length has been assumed. The actual distribution, if different to that assumed, would effect the estimations over the length of the pile. Below the pile tip, there would be no difference.

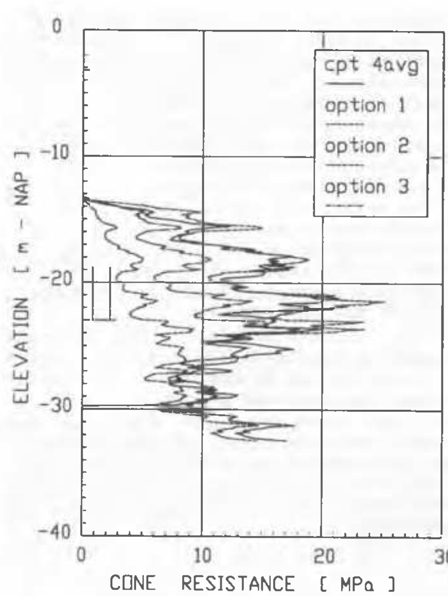

Fig. 10. Predicted and measured average CPT results from stage 4