STATNAMIC LOAD TESTS ON LARGE DIAMETER CASING PILES, EXCECUTION AND INTERPRETATION

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The use of bored, large diameter casing piles with base grouting, was a first time application in the Netherlands. Therefore it was decided to use CPTs as a way of checking the influence of the installation of the pile on the surrounding soil. A total of three piles were instrumented and tested on site by means of a static load suitability test and the deformations of all piles were monitored during construction up to the actual completion of the works. In order to get information on the pile behaviour under even larger loads two extra piles were tested by means of a statnamic load test with a 16MN device. This paper describes the execution and interpretation of the statnamic load test results and the results of the numerical modelling of the tests with the finite element program Plaxis.

INTRODUCTION

The railway extension project between three major Dutch cities, The Hague, Rotterdam and Utrecht, was commissioned by the Dutch railway authority Prorail in 2005. Near the city of Utrecht the extension includes the realization of a new embankment for 4 railroad tracks and a total of 20 new bridges. As a result of these bridges a safe passage is provided for the people living in the new residential area of Leidsche Rijn.

During the first phase of the project in 2005, a total of 83 piles were installed. In 2008, an additional 17 piles were installed for the second stage of the project. This paper describes the characteristics of this pile system by means of the chosen execution method and several checks on the final result. At each bridge site a number of Cone Penetration Tests (CPTs) were performed prior to pile installation in according with Dutch geotechnical standards. An assessment of pile installation effects was done based on CPT results before and after pile installation. At bridge number 6, three piles were instrumented with vibrating wire strain gauges and static suitability load tests were performed. After installation all piles were monitored during construction and also for a period after finishing the construction of the bridges.

In November 2008 two 16MN Statnamic load tests were carried out on sacrificial piles. The results of all tests, both static and statnamic, have been used to fit the numerical modelling of the test method with the finite element program Plaxis.

PILING SYSTEM AND EXECUTION

In the original client design all bridges had piled foundations. The foundations of abutments and footings consisted of thick concrete slabs with a large number of driven prefab concrete piles as are commonly used in the Netherlands. Since the bridges themselves were supported by columns of 1.2m in diameter an alternative design was made to use bored casing piles with a diameter of 1.65m, one pile below each column. Instead of using 80 prefab concrete piles, columns could be constructed on 6 of these casing piles. Also the heavy concrete slab (for which dewatering and additional temporary facilities were necessary) could be omitted.

The alternative foundation had to meet the strict client requirements. The piles have a design pile load of 12,000kN, but should also have a vertical deformation less than 10mm during train passage. Since bored piles normally have rather feeble load-displacement behaviour, it was deemed necessary to equip the piles with a grouting device at the pile tip.

The casing piles were bored without a stabilising fluid such as bentonite. During drilling and removing the ground inside the casing it was therefore essential that a higher water level was maintained in the casing than the actual groundwater head at the pile tip. To minimise the risk of disruption of the ground at the pile tip the piles were equipped with a grouting device that was injected after hardening of the concrete of the piles. By filling the grouting device under high pressure it was possible to pre-stress the pile tip (and hence the entire pile) to guarantee a stiffer load-settlement behaviour.

The execution method of the casing piles is presented in Figure 1.

SOIL CONDITIONS

The sub-surface along the route consists of a Holocene clay and peat layer that varies in thickness from 1m to 7m overlaying a Pleistocene sand layer with a thickness of more than 40m. The cone resistance in the sand layer varies from 5MPa (loose sands) to over 15MPa (medium dense to dense sands).

PILE DESIGN

Bearing capacity

In the Netherlands the calculation of all piles is based on the Dutch standards NEN670 and NEN6743-1. An example of this calculation method regarding the bearing capacity is included in EN 1997-2:2007 (E) Annex D7. This method is based on CPT results and application of α_p (point) and α_s (shaft) pile factors. These factors are given in the standards for a limited number of piles and are based on static tests that have been performed on piles over the last 30 years. The piles mentioned in the standards are:

- soil displacement type piles (driven piles)
- piles with limited soil displacement
- soil replacement piles (bored piles)

For soil displacement piles a typical value of the factor α_p is 1.0 and a typical value of factor α_s is 0.010 – 0.012. For soil replacement piles these factors vary from 0.6 to 0.8 and from 0.005 to 0.006 respectively.

For the casing piles there were no test results available in the Netherlands. Outside the Netherlands the bearing capacity of these piles is normally established based on a combination of experience, ground conditions and static pile load tests. There was no knowledge available on the correlation between CPT results and the obtainable pile capacity. As a result the original pile design was based on the pile factors for CFA-piles, a conservative design approach.

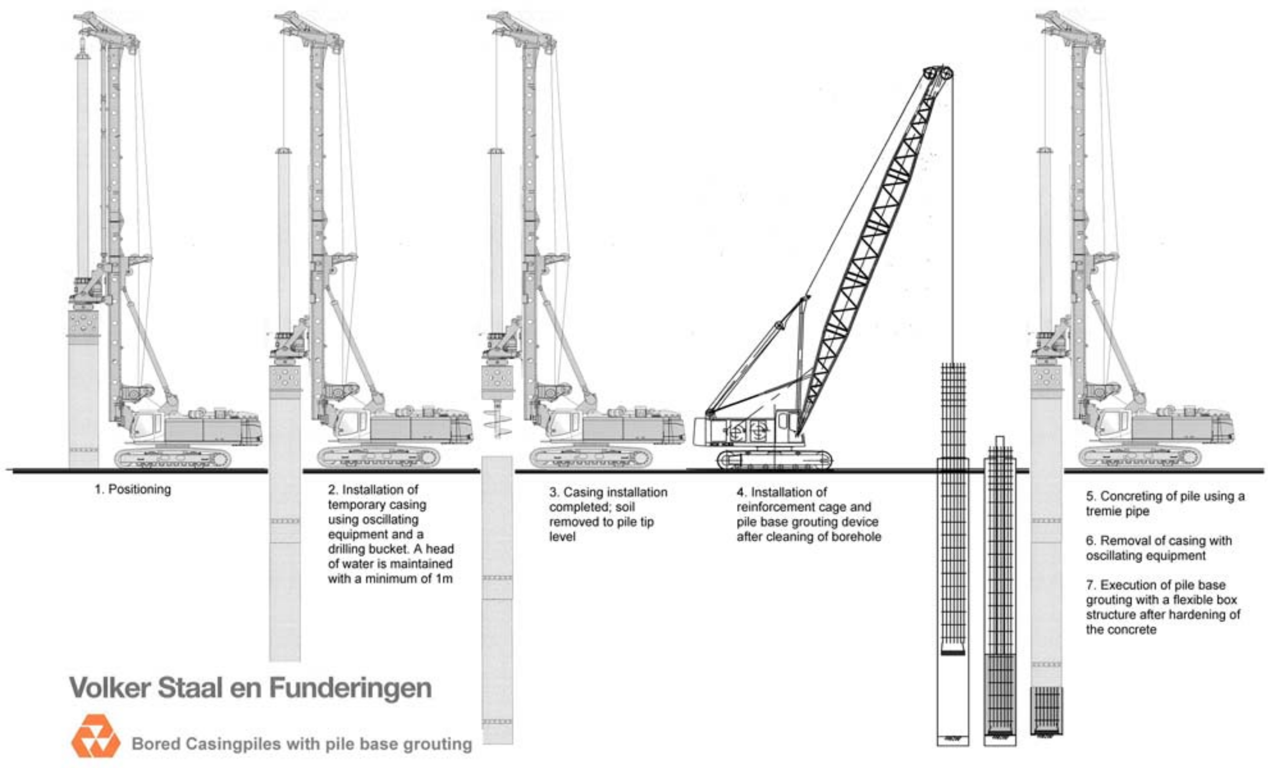

Figure 1: Pile execution method

Load-displacement behaviour casing piles

For three types of piles the load-displacement curves are presented in the Dutch standards. These curves are also based on pile load tests and are available for the same pile types as mentioned previously.

For the casing piles there were no test results available in the Netherlands. In order to examine whether the casing piles met the required stiff load-displacement behaviour, three suitability tests were carried out. On two piles a load of 6,000kN, equal to the service load, was applied. The third pile was tested to the design load of 8,000kN.

DESIGN BASED ON CPT'S BEFORE AND AFTER PILE INSTALLATION

In order to establish the influence of the pile installation on the ground conditions at each bridge site four CPT's were carried out at a very close distance to one of the piles. By comparing the CPT results before and after pile installation it is also possible to calculate the theoretical bearing capacity of the piles. The Dutch standards mention that under certain conditions this is an accepted calculation method. When the results of CPTs that were carried out after the installation of the pile are used, the factor of α_p is 1.0 and of α_s is 0.010. One of the conditions is that the CPT has to be carried out within a distance of one meter from the pile outside surface at ground level.

As a result of "normal" slope deviations of the CPT rod however, we do not consider this requirement to be strict enough. We believe that the CPT must be within the influence area of the pile (2D of the pile). For this reason the CPTs have been carried out equipped with a double inclinometer. As a result the exact position of the cone in the depth is known. At all locations the CPTs started at a distance of approximately 0.25m from the edge of the pile. Based on the results of the inclinometers it was established that the CPT results were obtained within a relevant distance to the piles.

From the results of the CPTs it could be concluded that the piles have neutral installation behaviour, this means on average there was only a limited increase or decrease of the cone resistance along the pile length. It should be stated that some variation in cone resistance is normal. In sandy deposits the standard deviation in the Netherlands is normally around 0.12 and at this specific project site it was approximately 0.15.

In Figure 2 the result of a CPT prior to pile installation is shown (black), in combination with the result of four CPTs that were carried out after pile installation.

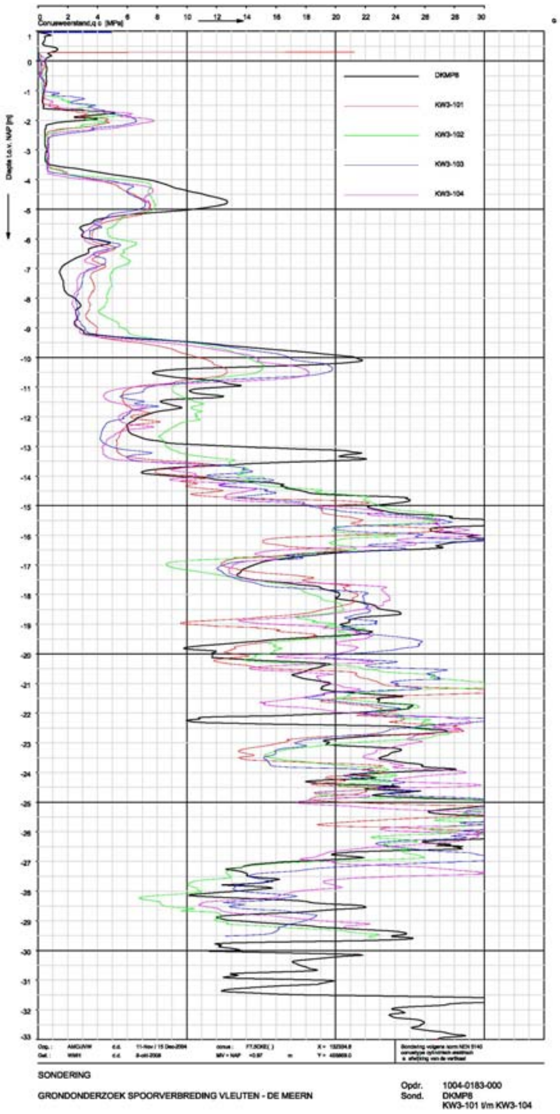

Figure 2: CPT's before and after pile installation

STATIC PILE LOAD TESTS

At bridge number 6 a row of three, 17.85m long, 1.65m diameter piles at a centre to centre distance of 3.75m were individually tested. The goal of these tests was verification of the load displacement behaviour up to 8,000kN. At three levels 3.6, 12.6 and 17.35m below the pile head 3 vibrating wire strain gauges were installed. A load cell was installed on top of the piles. Vertical displacements of the pile heads were measured by high accuracy levelling. At a level of 12.6 and 17.35m below the pile head tell-tales were installed.

The reaction frame with deadweight of 1,000kN was anchored by 8 Gewi-anchors with a capacity of 1,250kN each.

Prior to pile installation one CPT was carried out at the centre of each pile. The cone resistance of these CPTs show a significant spatial variation in vertical and horizontal direction which reflects the nature of the sand layers. After pile installation 4 CPTs were performed at 4 sides of each pile to detect production process anomalies. These CPTs started at GL at 0.25m distance of the pile shaft and the average deviation from the pile shaft at pile tip level was 1.1m. The average cone resistance of the CPTs executed after pile installation was over the pile length 20 – 60% higher and at the level just below the pile tip level the average cone resistance was 20% less than the CPTs before pile installation. The reduction of 20% is within natural variation of these sands but the local increase by 60% is not. It is concluded that there is no proof of anomalies during execution of the piles but there is a noticeable improvement of the soil conditions over the pile length.

Based on the 3 CPTs before pile installation the ultimate bearing capacity of the piles was estimated at 20,000kN.

The piles were loaded in steps of 1,000kN. The load was then kept constant for 1 hour, a time that was extended if the deformation rate was more than 0.3mm/h up to a maximum of 4 hours. At a load of 6,000kN the piles were unloaded to 4,000kN and reloaded to 6,000kN in steps of 1,000kN. Only one of the piles was loaded with an extra 2 steps of 1,000kN up to 8,000kN.

MEASUREMENTS

The measured load at the pile head versus the pile head displacements are presented in Figure 3. The shaft friction over the two sections between the strain gauges is presented as the shaft force versus the pile tip displacement measured by the lower tell-tale in Figure 4. The top section is from 3.6 to 12.6m below the pile head and the lower section is from 12.6m to 17.35m below the pile head.

During the loading of one pile the maximum vertical pile head displacement of the other 2 piles was measured. These additional deformations of the piles varied from 0.32 to 0.44 mm.

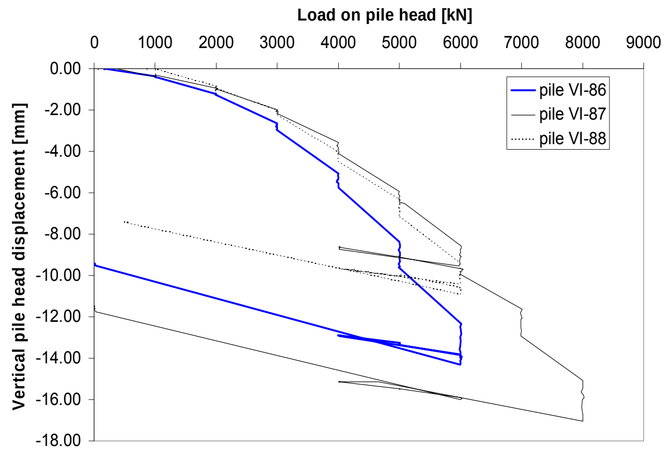

Figure 3: Load displacement curves of the pile heads

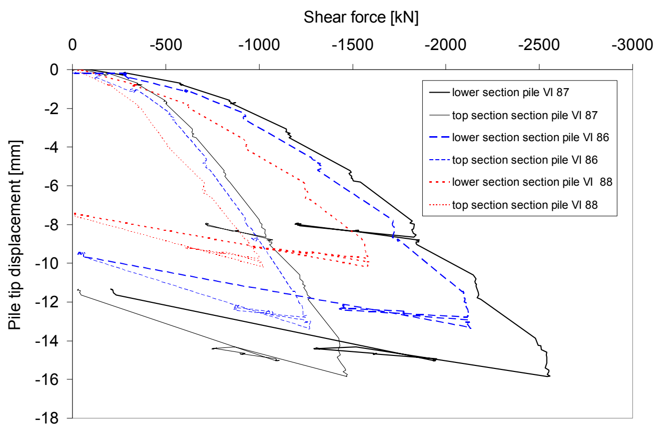

Figure 4: Load displacement curves of pile shaft sections

At 6 bridges the vertical deformation of the piles has been monitored on the long term. The total vertical deformations after 1 year of train passages are given in Table 1.

Table 1: Average settlement after 1 year of train passages

Bridge	Best estimate updated prediction [mm]	Measured [mm]	Ratio Predicted /measured
3	2.3	2.8	0.82
4	3.9	5.6	0.70
8 West	4.2	5.6	0.75
8 East	3.1	2.8	1.11
9	1.9	2.2	0.86
12	4.2	2.9	1.45
		Average	0.95
	Coefficient of Variation		0.28

STATNAMIC LOAD TESTING

Introduction

In November 2008 two Statnamic load tests were carried out on sacrificial test piles that had been installed in 2005. Originally it was intended to test these piles to refusal by means of a static load test. Such a test would have required a load of approximately 20,000kN, even though the piles have a limited length of 13m.

The introduction of a 16MN Statnamic device in the Netherlands by Fugro made it possible to test the piles to loads that would approach the ultimate bearing capacity of the piles. In a Statnamic load test pile loading is achieved by launching a reaction mass. This mass is only 5% of the weight needed for a static load test. The loading is perfectly axial, the pile and the soil are compressed as a single unit and the static load-displacement behaviour of the pile can be determined if a series of tests is performed.

Given the fact that the information of the static load test up to a load of 8,000kN was already available, the two test piles were only tested once with the maximum load of approximately 16MN.

Execution of the tests

The general description of the statnamic test has been given by Bermingham et al (1992). Four phases can be distinguished:

1. Prior to test; a piston with fuel is placed on the pile head. The cylinder with reaction mass is placed over the piston, leaving a pressure chamber inside. Around the reaction mass a container is erected and filled with gravel.
2. The fuel is ignited and pressure builds up. Cylinder and reaction mass are launched. The reaction force on the pile is measured as well as pile displacement.
3. Space under the cylinder and reaction mass is filled with falling gravel.
4. Cylinder and reaction mass fall on top of gravel and do not load the pile.

The test procedure itself proceeds according to the draft European guideline (Hölsher and van Tol, 2009)

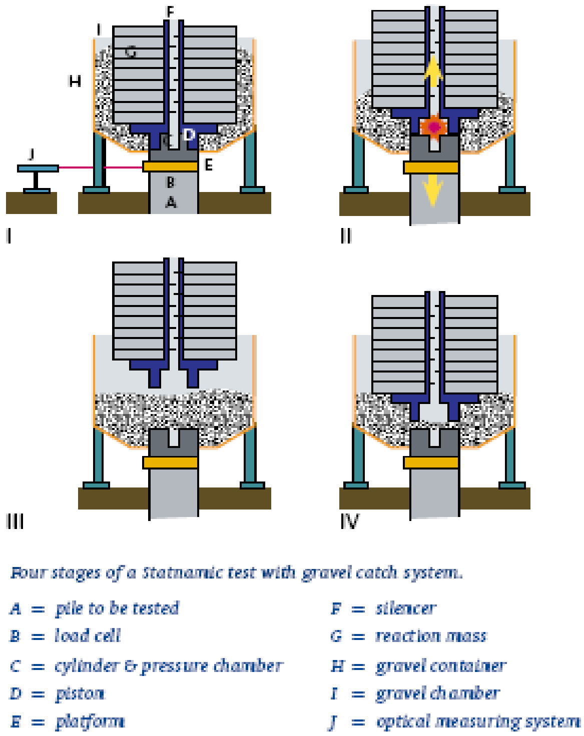

Figure 5: Stages Statnamic test

Figure 6: Statnamic test

Analyses of the test results

Tests were analyzed according to the Unloading Point Method (UPM) originally given by Middendorp et al (1992). Correction of the statnamic load – settlement curve has been made for inertia effects and damping. The damping correction was initially based on the average damping between the maximum load and unloading point. A correction has been applied to obtain a smooth hyperbolic curve. The original and corrected load-settlement curves are given in Figure 7.

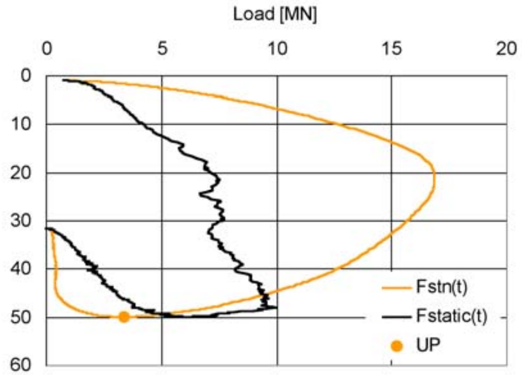

Figure 7: Results of the Statnamic load test where Fstn(t) is the measured load on the pile head and Fu(t) is the derived static pile resistance

The total load-settlement curve has been constructed in various ways. Curves according to Middendorp et al and equation (4) are given in Figure 8. In these curves a model factor of 0.92 has been applied. The model factor is in accordance with the draft European interpretation Guide and covers loading rate effects in the bearing sand layer.

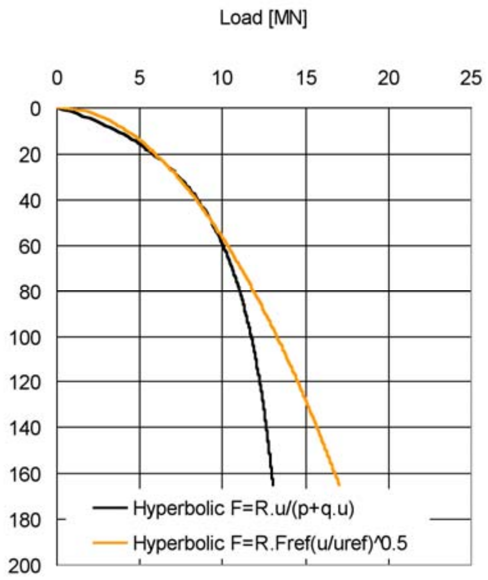

Figure 8: Derived static load-settlement curve

NUMERICAL MODELLING OF STATNAMIC LOADING TEST

For the numerical analysis of the load test an axis symmetrical model was made using Plaxis 2D V9. For the analysis of the first statnamic test a relatively detailed soil layering was applied, based on a direct interpretation of the CPT data in combination with table 1 of Dutch standard NEN 6740. Model parameters were calibrated with respect to the static load test carried out in 2005, assuming that both the piles in the static tests (with a length of 18m) and those in the statnamic tests (with a length of 13m), were positioned in the same geologic stratigraphy. In the prediction of the first statnamic test, the displacements were largely over predicted to be between 130 en 180mm, where the actual displacement was about 50mm.

Given this observation, sensitivity analyses with the model, and the applied parameters were done and evaluated. A first observation in this analysis was that the actual loading time during the test was a little shorter than assumed in advance, and subsequently did contain less energy; partially explaining the difference between prediction and test. Further back-analysis indicated that the actual friction angle, of the Pleistocene sand layer at the pile toe, must be higher than first assumed, i.e. a better match was found for a friction angle ϕ = 38˚ instead of 35^{o}. Subsequently the dilatancy angle was adapted and increased up to ψ = 8˚ for this layer. Further the parameters for the small strain stiffness model that was applied, see Benz (2007), were optimized indicating that with $\gamma_{0,7}$ = 1.0 E -4 a better match was found. In addition to that, the damping factors were slightly increased up to Rayleigh α = 1.0 E-3 and Rayleigh β = 1.75 E -3, see Zienkiewicz (1997).

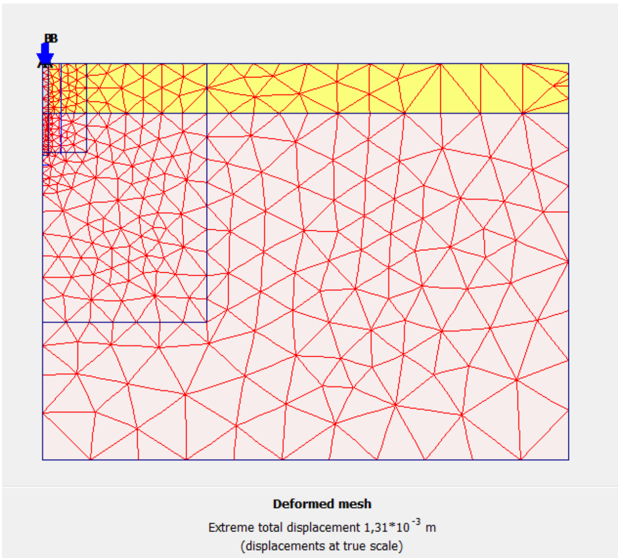

Figure 9: Finite Element model for dynamic load test

Furthermore some details in soil layering were ignored as some of the very soft layers near the soil surface seemed to destabilize during the analysis. Finally, only the difference between the soft Holocene upper layer and the much stiffer Pleistocene layer underneath was maintained, see Fig. 9. Variation with different schemes indicates that these measures, that largely stabilized the calculation process, seemed to have only a minor influence on the load displacement description.

With this model the pile was analyzed both statically and dynamically, in order to derive a comparison with the results of an affined static load test that according to NEN 6743 would require a total settlement of the pile head of 0.1 D (0.165 m). The numerically calculated load capacity based on the static analysis indicates a bearing capacity of:

$$F_{,d} = 2\pi \cdot 2{,}988 = 18.78 \text{ MN} \qquad (1)$$

Note that the output of Plaxis presents the load per radial, so this result needs to be multiplied with 2π, to obtain the full bearing capacity of the pile.

By comparison, if the pre-loading effect of grouting the pile tip would be disregarded, the numerical results are slightly less, but for much lower advance stiffness.

$$F_{,d} = 2\pi \cdot 2{,}710 = 17.03 \text{ MN} \qquad (2)$$

The analysis indicates that the effect of pre-stressing the pile would decrease the deformation by approximately 27mm.

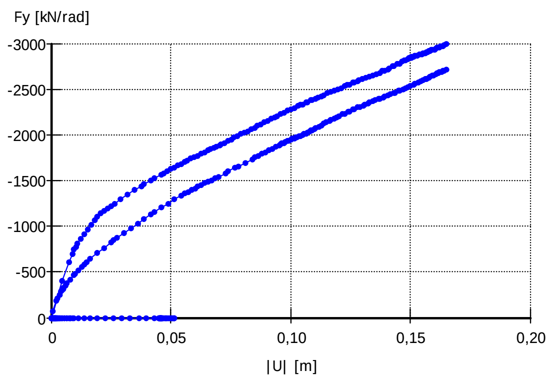

Figure 10: Simulation of Static analysis of the test pile configuration (13 m pile) with Plaxis; with (upper curve), or without base grouting of the pile toe (lower curve), (Plaxis output loading per radial)

Loading capacity back-analyzed from the dynamic analysis of the load test

From Fig. 10 it can be inferred that a bearing capacity as such is not a deterministic value but must be considered with respect to deformation.

According to Dutch standard NEN 6743-1 the applicable deformation is 0.1 D_{eq}, i.e. in this situation 0.165m. As a result of the short duration of a statnamic test the dissipation of excess pore water pressure will be disabled. Therefore the statnamic test in essence must be regarded as an undrained test. Numerical comparison of a drained and an undrained load test indicates that for the field test a reduction factor to 0.84 needs to be applied. Please note that this effect might lead to a controversial interpretation. The lack of drainage would lead to a limitation of the bearing capacity of the pile toe, whereas, due to dilatancy effects the shaft friction will be higher. Overall the effect of increasing shaft friction is dominant. For that reason the reduction factor must be interpreted as a reduction factor for the load capacity.

In Fig. 11, the characteristic load displacement curve based on the back-analysis with Plaxis is given, that may be compared to Fig 7. The overall agreement seems to be excellent. The only drawback in this comparison is that it seems to be difficult to represent the elastic response at the end of the loading, which in the numerical model lags behind. This effect however does not have much influence on the overall interpretation with respect to the bearing capacity.

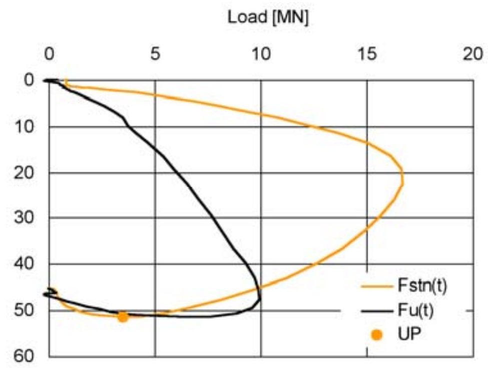

Figure 11: Results of the dynamic deformation analysis back-analysed with Plaxis, evaluated with the UPM methodology to derive the maximum pile loading during the test

Using the same procedure as for the direct interpretation of the Statnamic test, the bearing capacity was back-analysed from the numerical analysis, i.e. the UPM method as explained in the previous paragraph. Based on several variations of the numerical analysis, and considering that the elements in the numerical model itself do not differentiate between pile elements and soil elements, it became apparent that to explain the test properly it is necessary to account for moving soil mass underneath the pile toe. Here a soil volume of 1 times the diameter and 0.6 times this depth was adopted. In comparison to more regular statnamic tests on smaller piles this effect is more dominant due to the large diameter of the pile. The result of the back analysis is indicated in Fig. 12.

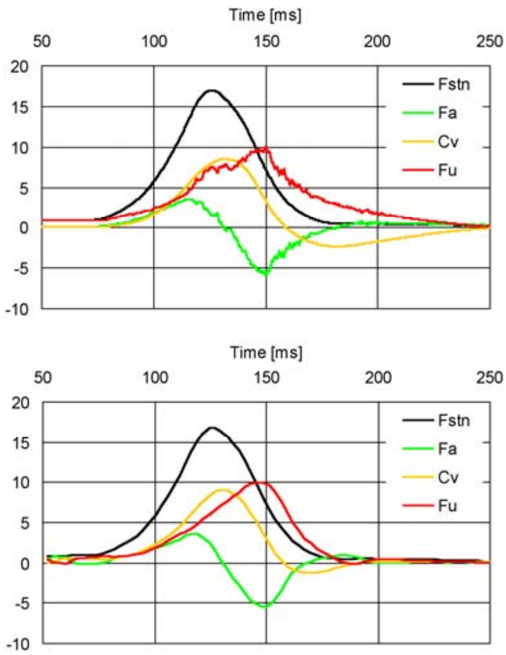

Figure 12: Results of Statnamic load test 17 nov 2008 (above), and numerical representation by Plaxis (bottom)

Based on the UPM evaluation of the numerical analysis a maximum pile load during statnamic testing was found of:

$$F_{r,l}\ (\delta = 49\ mm) = 9.73 \text{ MN} \qquad (3)$$

In order to compare this load with the ultimate bearing capacity according to a CPT or a static load test, it is necessary to consider not only the drainage effect, but also the fact that the deformations derived with the Statnamic test do not satisfy the necessary deformation for a static load test, that requires a displacement of 0.1 D_{eq}, or in this case 0.165m.

Comparing the load displacement curves in Fig. 10, it seems feasible to assume a hyperbolic shaped load displacement curve according to:

$$F_{r,\delta} = F_{ref}\left(\frac{\delta}{\delta_{ref}}\right)^m$$

(4)

For displacement in sand a factor m = 0.5 is not uncommon, and in this case seems to be sufficiently conservative.

Based on the above assumptions, correcting for the drainage effect and extrapolation for the appropriate deformation, the bearing capacity of the pile is calculated as

$$F_{r,0,1D_{eq}} = 0.84 \cdot 9,73\sqrt{\frac{0.165}{0.049}} = 15.0 \text{ MN} \qquad (5)$$

Comparing this value with the result of a direct analysis for a static loading this it is concluded that

$$15.0 \text{ MN} < F_{0,1Deq} <= 18.78 \text{ MN} \qquad (6)$$

CPT RESULTS TEST PILES

At the test site additional CPT's were performed both before and after pile installation. From the results of these CPT's an ultimate bearing capacity was calculated using the Dutch standard NEN6743-1. The average bearing capacity for the test piles was 18.74MN.

CONCLUSIONS

The use of bored, large diameter casing piles with pile tip injection was a first in the Netherlands. Using CPT results, pile load tests (both static and statnamic) and the monitoring results of the deformations of all piles during construction, a very good understanding was reached regarding the ultimate bearing capacity and the load-settlement characteristics of these piles.

The static load-settlement curve derived from the statnamic test depends strongly on the interpretation method especially on the selection of the damping parameter. The averaging procedure to determine C_4 according to the draft European interpretation Guide does not result in a reliable curve. Selection of a smaller damping parameter does supply a smooth hyperbolic curve as expected. For large diameter piles it is recommended to apply such a procedure.

The numerical modelling of the Statnamic tests with Plaxis made a better understanding of the actual test results possible. It was concluded that the Unloading Point Method underestimates the bearing capacity of large diameter piles, mainly due to neglecting the influence of the moving soil mass beneath the pile.

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