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Reduction of the Cone Resistance caused by the installation of CFA piles

Réduction de la résistance du cône causé par l'installation des pieux, type CFA

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ABSTRACT
In The Netherlands reduction coefficients are prescribed in order to account for the quality decline of the soil due to the installation of continuous flight auger (CFA) piles. In this paper the results of cone penetration tests (CPT's) are compared that have been made before and after the installation of CFA piles. The regulations and prescribed installation factors in the Dutch code NEN 6743 do not appear to be too conservative. The installation effect is significant, and not constant around the pile, and increasing with decreasing distances from the installed CFA pile.

RÉSUMÉ
Coefficients de réduction sont prescrit dans les Pays-Bas pour régler la diminution de qualité de la terre comme conséquence de l'installation des pieux du type CFA. Dans cette contribution les résultats d'essais pénétromètres à cône (CPT's) sont comparé qui sont exécuté avant et après l'installation des pieux CFA. Les règles et les prescrit facteurs d'installation dans le code des Pays-Bas, NEN 6743, ne paraît pas trop prudent. L'effet d'installation est significatif et n'est pas constant autour du pieu, et augmente avec les distances diminuantes du pieu CFA installé.

1 INTRODUCTION

In the 1970s a pile system using a continuous flight auger (CFA pile) appeared on the Dutch market as an alternative to driven cast in situ piles. Screwed or auger piles have advantages as compared to other pile systems, such as the absence of vibrations in the surrounding soil or an important reduction of noise during the pile installation. The CFA pile must however, with respect to the load-settlement behaviour, be considered as a soil replacement pile.

In The Netherlands, CFA piles are still the most popular type of screwed pile. The design method for the calculation of the bearing capacity of CFA piles in The Netherlands is based on the results of cone penetration tests (CPT's). However, reduction coefficients are prescribed in order to account for the quality decline of the soil caused by the installation of the piles. According to the Dutch code NEN 6743 the reduction coefficients may be omitted in case of additional CPT's to be carried out after pile installation, provided that the verification is done on the basis of the results of additional CPT's made within 1 m distance from the installed pile.

An important question is whether a reliable design can be made based on the CPT's performed after the installation of the piles. This is especially interesting for contractors that do pay a lot of attention to their piling work and that use for example very powerful equipment, making the piles more comparable with displacement piles. In this paper the magnitude of the prescribed reduction coefficients in the Dutch code is checked on the basis of field measurements of a number of projects in the southern part of The Netherlands. The focus is especially directed to the installation effects and the influence of the distance of the CPT's to the installed piles.

2 DUTCH CODE NEN 6743

NEN 6743 presents a method for the evaluation of the ultimate and serviceability limit states for piled foundations based on the results of CPT's (Everts & Luger, 1997). The total ultimate pile resistance R_u, the base resistance R_b and the shaft friction R_s at the location of CPT i is derived from:

$$R_{u;i} = R_{b;i} + R_{s;i} \quad (1)$$
$$R_{b;i} = A_b \cdot q_{b;i} \quad (2)$$
$$R_{s;i} = \Sigma A_s \cdot q_{s;i} \quad (3)$$

where:
$R_{b;i}$ is the ultimate base resistance of the pile determined from the results of CPT i;
$R_{s;i}$ is the ultimate shaft resistance determined from the results of CPT i;
A_b is the cross sectional area of the pile base;
$q_{b;i}$ is the ultimate unit base resistance from the results of CPT i;
A_s is the circumferential area of the pile shaft in the layer in which the pile shaft friction has been assumed;
$q_{s;i}$ is the ultimate unit shaft resistance determined from the results of CPT i;

To determine the base resistance from the results of CPT's Koppejan (1948) assumed the following:

- the soil around the pile base fails according to slip surfaces that have the shape of a logarithmic spiral;
- the logarithmic spiral can be divided in three trajectories: I, II and III. Figure 1 shows the trajectories and their positions;

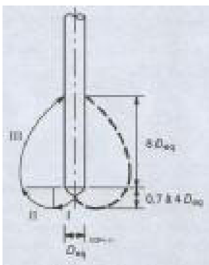

Figure 1: Base resistance calculated in three trajectories

- the contribution to the base resistance of the soil layers below base level is equal to that of the layers above it (contribution I + II = contribution III);
- the contribution of the soil below base level consists of two equal parts (contribution I = contribution II).

According to the Dutch code NEN 6743 the ultimate unit base resistance q_b must be obtained by calculating:

$$q_b = \tfrac{1}{2}\,\alpha_b\,\beta\,s\left(\frac{q_{c;I;mean} + q_{c;II;mean}}{2} + q_{c;III;mean}\right) \quad (4)$$

where:

q_b is the ultimate unit base resistance

$q_{c;I;mean}$ is the mean value of the cone resistance q_c in trajectory I that runs from the base level to a level that is at least 0.7 times and at most 4 times the equivalent diameter (D_{eq}) deeper. The bottom trajectory I (the 4D zone) must be selected within the above mentioned limits in such a way that q_b is minimal;

$q_{c;II;mean}$ is the mean value of the cone resistance q_c in trajectory II that runs from the bottom of trajectory I to the base level, whereby the value used for the cone resistance must never be higher than the previous value in the trajectory (also the 4D zone);

$q_{c;III;mean}$ is the mean value of the cone resistance q_b in trajectory III that runs from the base level to a level that is 8 times the equivalent diameter (D_{eq}) higher, whereby in the same way as for trajectory II the value used for the cone resistance must never be higher than the previous value in the trajectory (the 8D zone). The starting value of the used cone resistance in trajectory III is the lowest value used for the cone resistance in trajectory II.

α_b is the installation factor for the pile base. For full displacement piles such as driven piles this factor equals 1.0;

β is the factor that takes into account the influence of the shape of the pile base;

s is the factor that accounts for the influence of the shape of the cross-section of the pile base.

According to the Dutch code NEN 6743 the ultimate unit shaft resistance q_s must be obtained by calculating:

$$q_s = \alpha_s * q_{c;z} \quad (5)$$

where:

q_s is the ultimate unit shaft resistance at depth z;

α_s is the installation factor for the pile shaft. For full displacement piles such as driven piles this factor equals 0.01;

$q_{c;z}$ is the cone resistance whereby values higher than 15 MPa that occur over a depth range of more than 1 m have been limited to 15 MPa and values higher than 12 MPa that occur over a depth range of less than 1 m have been limited to 12 MPa.

3 DESIGN RULES FOR CFA-PILES

The Dutch code NEN 6743 contains for CFA piles the following specific regulations:

- trajectory III must start with a cone resistance less than or equal to 2 MPa, unless the results of a CPT are used, which has been carried out at a distance of 1 m from the pile after pile installation;
- the installation factor for the pile base is for CFA piles 0.8. It is allowed to use a higher pile factor, if it is demonstrated by calculations that $q_{b;after} \geq q_{b;before}$ whereby $q_{b;after}$ has been calculated with $\alpha_b = 1.0$ and with the results of CPT's nearby at least three installed piles that have been made after the installation and at a distance of 1 m from the side of the pile;
- the installation factor for the pile shaft in sand and gravely sand is for CFA piles 0.006. This maximum value of α_s shall be applied if q_c values have been used from CPT's that have been made near the piles before pile installation. If q_c values are used from CPT's that have been made near the piles after pile installation, the maximum value of $\alpha_s = 0.01$.

It follows that to determine the ultimate shaft resistance of a CFA pile the Dutch code NEN 6743 reckons with a reduction of the cone resistance of 40 % due to the installation of the pile ($\alpha_s = 0.006$ in stead of 0.01). This is because the determination of the ultimate shaft resistance according to the Dutch code NEN 6743 is based on the average cone resistance and the expected reduction of the cone resistance therefore follows directly out of the ratio between the installation factors.

It is not allowed to draw a similar conclusion for the pile base just like that. The pile base resistance is not only determined by the average cone resistance, but also by local declines of the cone resistances in the zone around the pile base. Moreover the value of $q_{c;III}$ in the calculation of the base resistance must be limited to 2 MPa. Although it seems that to determine the ultimate base resistance of a CFA pile the Dutch code NEN 6743 reckons with a reduction of the cone resistance of about 20 % due to the installation ($\alpha_p = 0.8$ in stead of 1.0), the Dutch code NEN 6743 in fact reckons due to the maximization of $q_{c;III}$ with a much larger reduction of the cone resistance than 20%.

4 VERIFICATION OF THE DESIGN RULES FOR CFA PILES

Verification of the relevant articles in the Dutch code NEN 6743 can be done by comparing the results of CPT's before and after the installation of CFA piles. However it should be kept in mind that:

- a natural variation in ground conditions exists. Although the results of CPT's can be reproduced rather good nowadays, a second CPT executed at almost the same location will never result in exactly the same cone resistances;
- there may be a difference in ground level. If CPT's executed after the installation of the CFA piles have been made from a lower level than the CPT's that were executed before the installation of the piles, this will result in somewhat lower cone resistances;
- the way CFA piles are installed will influence the cone resistance of the CPT's that are made afterwards. This will be further discussed in this paper;
- the distance between the installed CFA pile and the CPT that is executed afterwards is important. This will also be further discussed in this paper.

The verifications were done with the information of foundation projects in the southern part of The Netherlands. The ground level at the different projects is some meters above sea level. Below ground level there are medium dense to dense sand layers up to a depth of 5 to 10 m, with locally loam and clay layers. Below these layers densely packed sand is encountered up to about 15 m below ground level, and below this dense sand layer there is another medium dense sand layer up to the maximum investigated depth, 20 m below ground level. The groundwater level is about 2 m below ground level. Figure 2 shows a typical CPT made before the installation of a CFA pile.

Table 1: Average cone resistances of 21 CPT's per m depth

depth [m sea level]	$q_{c;mean;before}$ [MPa]	$q_{c;mean;\,after}$ [MPa]	Reduction Factor
0 tot –1	8.50	6.52	0.77
-1 tot –2	7.25	5.55	0.77
-2 tot –3	6.00	5.17	0.86
-3 tot –4	6.49	4.57	0.70
-4 tot –5	8.06	5.30	0.66
-5 tot –6	7.71	5.25	0.68
-6 tot –7	10.74	6.27	0.58
-7 tot –8	13.50	7.88	0.58
-8 tot –9	14.89	9.07	0.61
-9 tot –10	18.70	11.99	0.64
-10 tot –11	23.42	19.04	0.81
average	11.39	7.87	0.69

5 INFLUENCE OF THE INSTALLATION OF THE CFA PILE

At a project where CFA piles were installed, it appeared that, due to a defect of the depth meter, the installed piles with a diameter of 0.45 m were not long enough. Before deciding to replace the piles or not, a number of CPT's were carried out at 0.5 m from the side of the installed piles. In all 21 CPT's carried out before and after installation of the piles, and situated practically at the same location, were available to compare. Figure 3 shows a CPT that was made after the installation of a CFA pile, at practically the same location as the CPT of figure 2.

Table 1 shows for every meter the average cone resistances before and after the installation of the CFA piles from sea level up to 11 m below sea level. It shows that the reduction of the cone resistance between 10 and 11 m below sea level appears to be significant smaller than at higher levels. At most locations this difference can be attributed to the decreasing effect of the installation towards and under the pile base.

According to the Dutch code NEN 6743 the ultimate base resistance can be calculated with the results of CPT's made after the installation of the piles. From there the value of the installation factor for the pile base α_b related to the CPT made before the installation of the pile can be back calculated by comparing the calculated ultimate base resistance before and after the installation of the pile. First of all the average cone

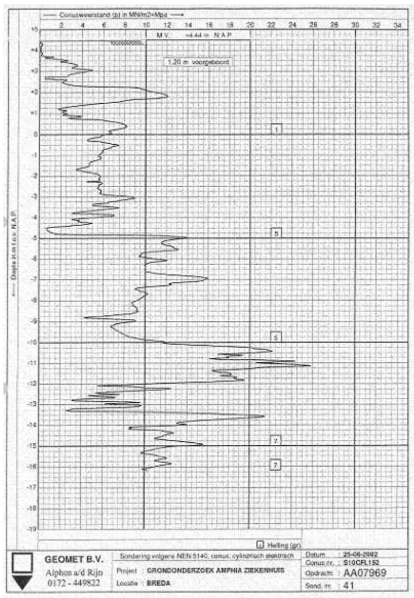

Figure 2: CPT made before the installation of a CFA pile

Table 2: Average reduction factors in different zones

Pile length from 0 to -11 [m sea level]	4D zone from –9 to –11 [m sea level]	8D zone from –5 to –9 [m sea level]	Friction zone from 0 tot –9 [m sea level]
0.69	0.74	0.61	0.67

resistances in the 4D/8D zone before and after the installation of the piles have been compared. To determine the reduction of the cone resistance around the pile base, a base level of 9 m below sea level is assumed for all piles. From there a zone of 2 m (~4D) below the pile base and 4 m (~8D) above the pile base is considered. Table 2 shows the calculated average reduction factors in the pile base and pile shaft zones. The reduction factor in the 4D zone is somewhat larger than in the other zones. This is possibly caused by the ending of the pile. It is striking that the influence of the installation on the cone resistance just above the pile base (the 8D zone) is larger than in the friction zone. The CPT's after the installation of the piles have after all been carried out from a lower level than the original CPT's and it is therefore more logic to expect the opposite. This may be explained by the effect of the lifting of the auger.

The calculated average reduction factor in the friction zone (0.67) can directly be compared with the ratio (0.60) of the in the Dutch code NEN 6743 mentioned factor α_s that goes with the CPT's made before installation of the piles (0.006) and made after installation of the piles (0.010). This comparison turns out to be positive for the CFA piles in this project, all the more if it is realised that most of the CPT's made after the installation of the piles have been carried out from a lower ground level than the CPT's made before the installation of the piles.

The calculated reduction coefficient in the 4D/8D zone 0.67 (the average of 0.74 and 0.61) will in general not be equal to the factor α_b. The factor α_b must in fact be back calculated by way of the base resistance calculated with the CPT's made before and after the installation of the piles. The factor α_b is particularly determined by the declines in cone resistances in the 4D/8D zone en less by the average value. For this project only a limited number of calculations made by a third party were available. It was concluded that the back calculated reduction factor (0.75) was smaller than the factor α_b (0.8) mentioned in the Dutch code NEN 6743. In this comparison $q_{c;III}$ = 2 MPa was used to calculate the mentioned 0.75. If this limitation of $q_{c;III}$ was not used, the calculated reduction factor would even have been much smaller than 0.75.

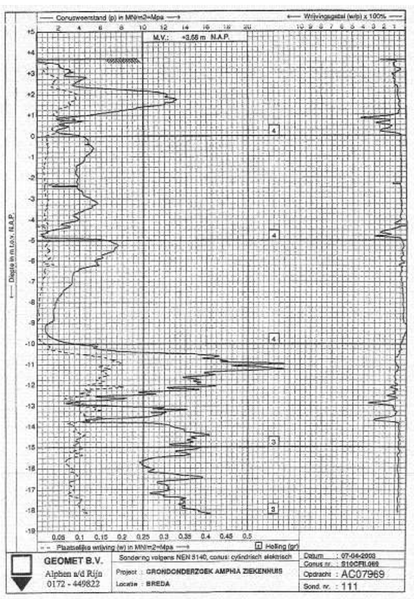

Figure 3: CPT made after the installation of a CFA pile

6 INFLUENCE OF THE ORIENTATION AND OF THE DISTANCE FROM THE CPT TO THE CFA PILE

At 10 project sites in The Netherlands, where CFA piles were installed by the same firm, an investigation was carried out to assess the influence of the distance between the CPT's and the installed pile and the orientation of the CPT's around the pile.

At one of the project sites in the southern part of The Netherlands the influence of the orientation of the CPT's made after the installation of the CFA pile was investigated. At three locations 1 CPT was performed in the centre of the pile before installation and 4 up to 7 CPT's were performed at different distances and with different orientations. The diameter of the pile auger was 0.362 m and the base level was 8 m below sea level. Figure 4 shows the results of one of the three locations, where 4 CPT's were made after installation at a distance of 0.7 m, centre to centre, around the pile and the result of the CPT made before the installation. The reduction of the cone resistance due to the installation of the CFA pile is considerable and appears not to be constant over the depth and not the same in all directions. The calculated reduction factors for the pile base vary between 0.34 and 0.59, and the reduction factors for the pile shaft vary between 0.69 and 0.76.

At the same site where the influence of the orientation of the CPT's made after the installation was investigated, three static pile loads tests were performed. Two CPT's were performed around the pile at 1.3 m centre to centre after installation and all other CPT's after installation at a distance of 0.7 m centre to centre. At each test location 1 CPT was carried out at the projected centre of the test pile before installation.

During the pile load tests the base and shaft resistance were measured with strain gauges along the shaft. The criterion for the ultimate resistance was a pile base displacement of 20 % of the pile diameter. All the calculations of the pile resistances were carried out with $\alpha_b = 1.0$ and $\alpha_s = 0.010$.

Comparing the calculated ultimate resistances based on the CPT's before installation and the CPT's after installation, shows that the installation effect is tremendous. The low calculated reduction factors were probably caused by problems during the installation process. The measured ultimate resistances are even lower than the minimum of the calculated values based on the CPT's after installation. With these results it seams difficult to determine which of the CPT's after installation gives reliable information for a re-design. All the calculated ultimate resistances are far to high.

The measured ultimate base resistance of the three piles is respectively 10 %, 19 % and 27 % of the calculated ultimate base resistance based on the CPT's before installation (the

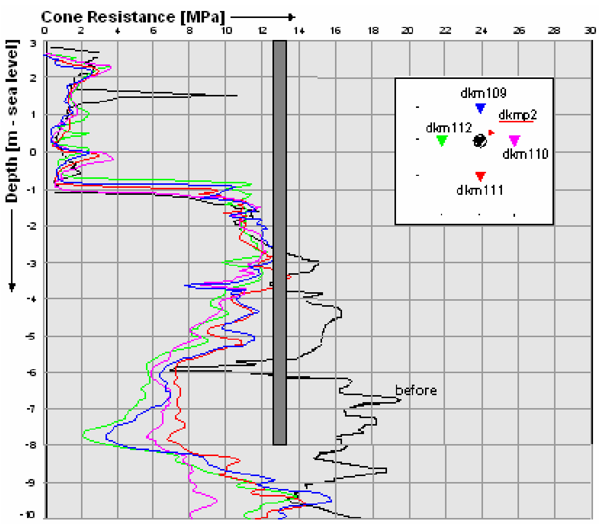

Figure 4: Results of 4 CPT's after installation at different orientations performed at 0.7 m from the pile centre

calculations of the pile resistances were carried out with α_b = 1.0 and α_s = 0.010) . These figures can be plotted in figure 5 at the vertical axis, representing the side of the pile on the horizontal axis. The value (10%) for one pile seams to be in good line with the calculated $q_{b;after}/q_{b;before}$ see figure 5. So it appears that for a reliable re-design one should extrapolate the CPT results at different distances to the side of the pile. Doing the same for the shaft gives 20 %, 39 % and 34 %. Again for the same pile the value of 20 % is a good extrapolation of the calculated $q_{s;after}/q_{s;before}$ at greater distances, see figure 5.

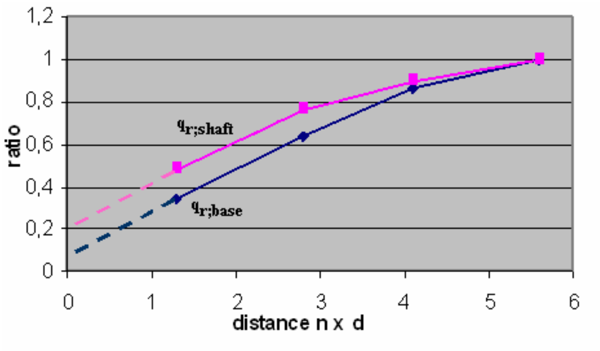

Figure 5: Ratio between the calculated $q_{b;after}/q_{b;before}$ and $q_{s;after}/q_{s;before}$ for one of the pile extrapolated to the side of the pile, based on the average of the CPT's

7 CONCLUSIONS

The results of CPT's that have been made before and after the installation of CFA piles, show a large scatter in the calculated reduction factors, both for the calculated average per CPT, and for the pro meter calculated average reduction coefficient. At few locations large reductions of the cone resistance were measured up to 1 till 1.5 m below pile base level. At some locations reduction coefficients were calculated ranging from 0.2 to 0.3 a few meters above pile base level. In those cases there was no clear relation with the magnitude of the original cone resistance. However the regulations and prescribed installation factors in the Dutch code NEN 6743 do not appear to be too conservative.

The installation effect is not constant around the pile, and increasing with decreasing distances from the installed pile. Based on three static pile load test and the CPT's at different distances and orientations after installation a reliable re-design can only be made when all CPT's are taken into account. For such a re-design one should carry out CPT's at different distances as close as possible to the installed pile, and at different orientations around the pile. The calculated ultimate resistances based on these CPT's, must be plotted in a graph, base and shaft separately as a function of the distance, and the average trend line must then be drawn through these values. The extrapolated value at the side of the pile leads finally to the correct re-design value. It is obvious that this procedure is not very practical, but in case of a poor quality of the pile installation, with a severe stress relieve in the soil, it is the only way to proceed. It should be investigated whether in case of a good pile installation this procedure holds. It does of course hold if no stress relieve occurs and the CPT's before and after result in the same cone resistances.

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