Some new insights with regard to load distribution in piles, based on a detailed interpretation of a large number of instrumented pile load tests

N. Huybrechts
Belgian Building Research Institute, WTCB-CSTC-BBRI, Belgium

J. Maertens
Jan Maertens & Partners bvba & Catholic University of Leuven, KUL, Belgium

ABSTRACT: During the last decade a large number of static load tests on instrumented piles have been performed in Belgium. A number of load tests performed by the BBRI since 1997, and some former load tests are analysed in detail and compared with the recent Belgian design rules for axially loaded piles according to EC7.

1 INTRODUCTION

Since the 1970's several pile load test campaigns have been carried out in Belgium. A general overview of these test campaigns and the types of tested piles, have been given in Holeyman et al (1997). Since 1997, a lot of supplementary scientific pile load test have been performed by the Belgium Building Research Institute (BBRI), in particular with the viewpoint to anticipate on the success of the soil displacement screw pile types on the Belgian market, and to support the establishment of a background document for pile design according to Eurocode 7 in Belgium (BBRI, 2008).
This contribution gives an overview of a number of the scientific pile load tests that have been performed by the BBRI in Belgium since 1997, and focuses in particular on the separation of the pile load in base resistance and shaft friction. Some data of former load tests on instrumented bored piles in Kallo in the 1980's have been re-analysed as well. The obtained data are compared with the recent rules for pile design in Belgium according to EC7 as described in (BBRI, 2008)

2 OVERVIEW PILE LOAD TEST CAMPAIGNS

2.1 *Pile load test campaign in Sint-Katelijne-Waver*

In Sint-Katelijne-Waver a real scale load test program on 30 piles was set up. It concerned 12 static load tests (SLT), 12 dynamic load tests (DLT) and 6 statnamic tests (STN) on 5 types of soil displacement screw piles and on precast driven piles installed in tertiary o.c. Boom clay. Figure 1 gives a typical CPT on the test site; on the same figure the two different pile installation depths (7.5 m and 11.7 m) are indicated as well.
These tests were performed in the framework of a BBRI research program (1998-2000). This project took place with the financial support of the former Belgian Federal Ministry of Economical Affairs, - which is actually called he Federal Public Service Economy - , and was carried out in collaboration with five Belgian piling companies (De Waal Palen, Franki Geotechnics B, Fundex, Olivier and Socofonda). A National Advisory Committee under supervision of prof. A. Holeyman (UCL) and prof. J. Maertens (KUL) guided the research program.
For a detailed overview of the test campaign set-up, the extended soil investigation campaing, the pile types, the load test procedures and the test results, reference is made to Holeyman (1998).

The normalised load settlement diagrams resulting from the instrumented load tests are summarised in figures 2 to 4.

On the vertical axis of these figures the pile head settlements are expressed as percentage of the pile base diameter. On the horizontal axis the measured pile base load $Q_{b,meas}$, the measured shaft friction $Q_{s,meas}$, and the total measured load Q_{meas} are expressed in relation to the calculated values of the ultimate pile base resistance $R_{bu,calc}$, the ultimate shaft friction $R_{su,calc}$ and the total ultimate pile resistance $R_{cu,calc}$ respectively.

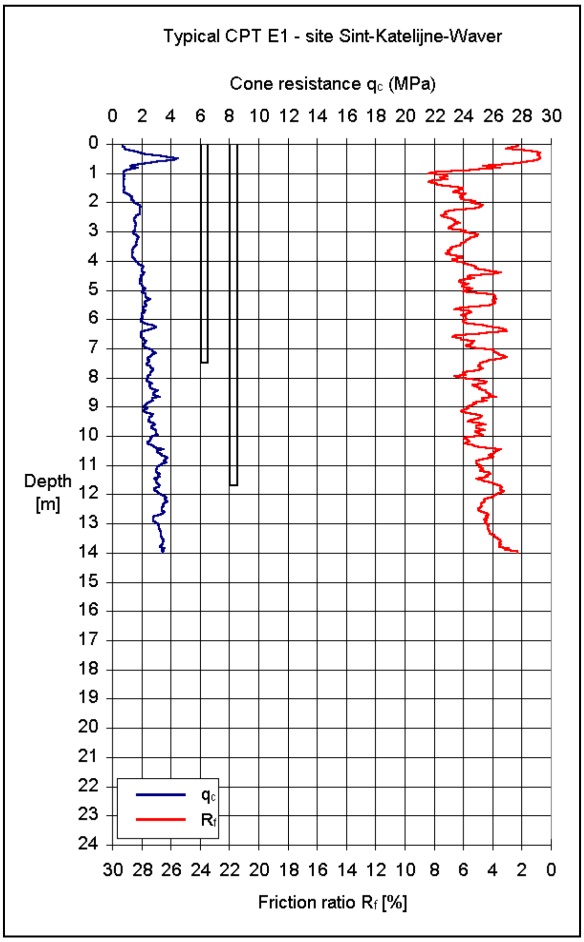


Figure 1 – CPT profile an pile lengths site Sint-Katelijne-Waver

These calculated values have been determined based on the CPT with electrical cone in the axis of each individual pile and according to the recent "Guidance rules for the application of EC7 in Belgium – part 1 : Geotechnical design in ULS for axially loaded compression piles based on CPT" (BBRI, 2008). The formulas to determine the ultimate pile resistances are summarised below. Nominal pile dimensions as fixed in these recent design rules have been applied for the piles in Sint-Kaelijne-Waver.

$$R_{cu,calc} = R_{bu,calc} + R_{su,calc} \qquad (1)$$

$$R_{bu,calc} = \alpha_b.\varepsilon_b.\beta.\lambda.A_b.q_b \qquad (2)$$

with

q_b (kN/m²) ultimate unit pile base resistance, calculated from CPT results with the De Beer method

A_b (m²) pile base cross sectional area;

α_b (-) an installation factor: an empirical factor taking into account the method of installation of the pile and soil type.

ε_b (-) a parameter referring to the scale dependant soil shear strength characteristics
$= 1 - 0.01\left(\frac{D_{b,eq}}{D_c} - 1\right)$ in the case of fissured Tertiary Clay, but always > 0.476
= 1 in all other cases

$D_{b,eq}$ is the diameter of the pile base; D_c is the diameter of the cone of the CPT (standard cone: 35.7 mm).

β (-) a shape factor introduced for neither circular nor square shaped bases

λ (-) a reduction factor for piles with an enlarged base

$$R_{su,calc} = \chi_s.\Sigma(\alpha_{s,i}.h_i.q_{s,i}) \qquad (3)$$

$q_{s,i}$ (MPa) ultimate unit pile shaft resistance
$q_{s,I} = \eta^*_{p,i}.q_{c,m,i}$

$\eta^*_{p,i}$ (-) empirical factor depending on the soil type ; values see table 1

$q_{c,m,i}$ (MPa) mean cone resistance (q_c) in layer i

χ_s (m) perimeter of the shaft

$\alpha_{s,i}$ an installation factor: an empirical factor introducing the effects of pile installation method, of the nature of the shaft's material and soil structure scale effects.

Table 1 - η^*_p (-)or q_s (MPa) values from BBRI (2008)

Soil type	q_c (MPa)	η^*_p (-)or q_s (MPa)	R_f (%)
Clay	1 – 4.5	$\eta^*_p = 1/30$	3 – 6 %
	>4.5	$q_s = 0.150$	
Loam (silt)	1 – 6	$\eta^*_p = 1/60$	2 – 3 %
	> 6	$q_s = 0.100$	
Sandy clay/loam (silt)	1 – 10	$\eta^*_p = 1/80$	1 – 2 %
Clayey sand/loam (silt)	> 10	$q_s = 0.125$	
Sand	1 – 10	$\eta^*_p = 1/90$	< 1%
	10 – 20	$q_s = 0.110 + 0.004*(q_c - 10)$	
	> 20	$q_s = 0.150$	

For the tertiary clay site in Sint-Katelijne-Waver the following values from the recent guidance rules have been applied in the calculated values in figures 2 to 4:

- α_b=1 for the driven precast piles and α_b=0.8 for soil displacement screw piles
- ε_b : see formula before
- $\beta = \lambda = 1$ for all piles
- $\eta_p^* = 1/30$ (clay)
- $\alpha_s = 0.9$ for all piles

The measured values of the pile base resistance and shaft friction have been deduced from pile deformation measurements with a retrievable extensometer device, using the Fellenius (2001) interpretation methodology in order to deal with a non linear stress-strain behaviour of concrete.

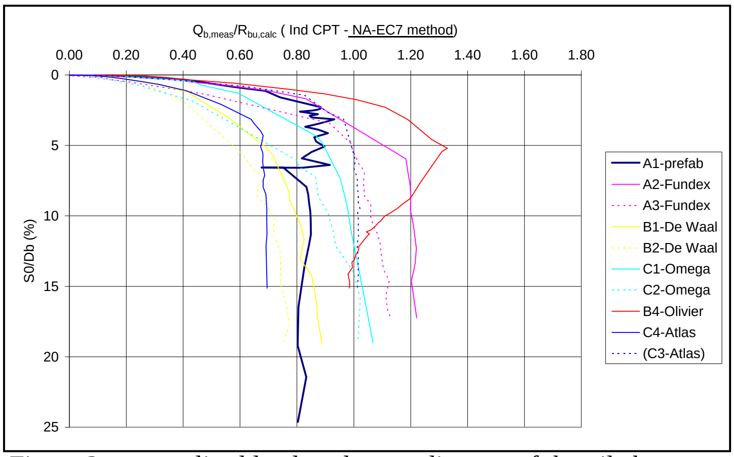


Figure 2 – normalised load settlement diagram of the pile bases in Sint-Katelijne-Waver (α_b = 0.8 for screw piles and α_b = 1 for driven precast piles have been applied)

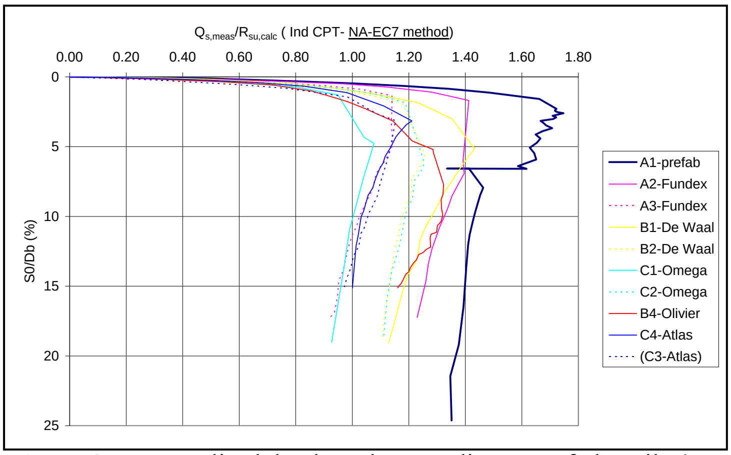


Figure 3 – normalised load settlement diagram of the piles' shaft friction in Sint-Katelijne-Waver (αs = 0.9 for all piles have been applied)

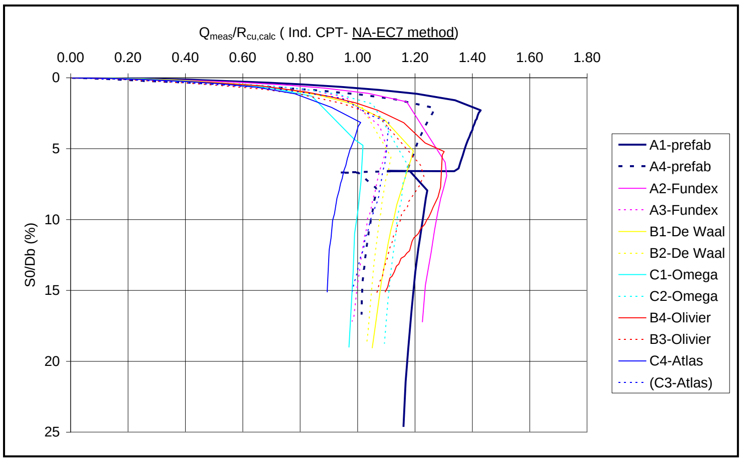


Figure 4 – normalised load settlement diagram of the total pile load in Sint-Katelijne-Waver

When one takes into account that a relative pile settlement of 10%D_b, with D_b the pile base diameter, has been put forward as conventional rupture load in the new design rules, one can conclude that:

- For the soil displacement screw piles the calculated base resistances corresponds well with the measured one, although the variation is rather high. The base resistances of these piles seem to be fully mobilised at settlements of about 15%D_b.
- The calculated pile shaft resistances seem to be somewhat too pessimistic at a settlement of 10%D_b. Although it can be stated that the ratio between measured and calculated shaft resistances evolves to 1 at larger pile displacements.
- For the driven precast piles, only one pile was instrumented. The calculated base resistance seems too optimistic, but this might partially be explained by the presence of residual stresses in the pile due to the installation. The total calculated pile capacity of the precast driven piles fits well with the measured data.

2.2 *Pile load test campaigns in Limelette (LIM I & LIM II)*

In the framework of an extension of the previous mentioned BBRI research project in 2000-2002, a similar extended real scale load test campaign on the same pile types was organised on a site in Limelette (LIM II). For details about this extended test campaign LIM II reference is made to Maertens & Huybrechts (2003)

A typical CPT on the test site is illustrated in Figure 5. The following layers have been identified:

- Quaternary loam (silt) : 1.0 m to ±6.2 m
- Sandy clay tot clayey sand : ±6.2 m to ±8.2 m
- Tertiary Ledian/Bruxellian sand = ± 8.2 m – …

The pile bases were installed in the sand layer at a depth of 9.5 m.

Similarly to the previous test campaign the normalised load settlement diagrams of the tested piles (10 soil displacement screw piles and 2 driven precast piles) are given in figures 6 to 8. On the same figures the normalised load settlement diagrams of a former test campaign in Limelette (LIM I) on three driven piles are given as well; it concerns a precast pile, a cast-in-situ pile and a closed end tubular pile.

For all the piles of the Limelette test campaigns (LIM I & LIM II), the calculated values have been determined based on the CPT with electrical cone in the axis of each individual pile and based on nominal pile dimensions as fixed in the recent design rules. For the soil layers in Limelette the following values from the recent guidance rules have been applied in the calculated values in figure 6 tot 8:

- α_b=1 for the driven piles and α_b=0.7 for soil displacement screw piles
- $\varepsilon_b = \beta = \lambda = 1$ for all piles
- $\eta_{pi}^* = 1/60$ for the loam layer at depth ±1 m to ±6.2 m

η_{pi}^{*} = 1/80 for the sandy clay tot clayey sand layer (±6.2 m to ±8.2 m)

- $q_{s,i}$ (MPa) = 0.110 + 0.004.(q_c-10) wit a maximum of 0.150 MPa for the sand layer (±8.2 m to pile base)
- $\alpha_{s,i}$ = 0.6 for the closed end tubular driven pile
- $\alpha_{s,i}$ = 1 for the other driven piles and the soil displacement screw piles

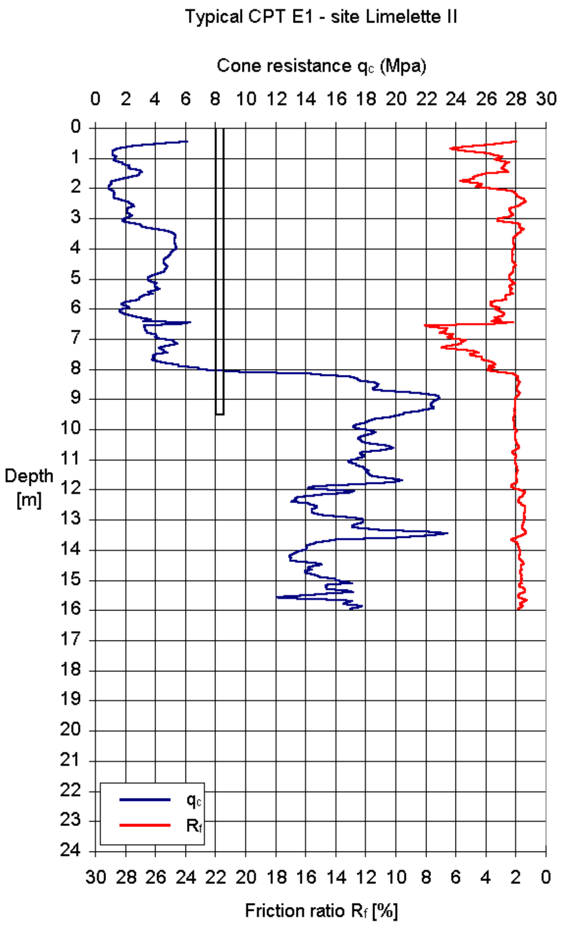


Figure 5 – CPT profile an pile length site Limelette

For the LIM II test campaign, the measured values of the pile base resistance and shaft friction have been deduced from pile deformation measurements with a retrievable extensometer device, using the Fellenius (2001) interpretation methodology in order to deal with a non-linear stress-strain behaviour of concrete. Furthermore, as several test piles were excavated after the load tests, the real pile dimensions and the concrete quality with depth have been taken into account in this interpretation.

For details with regard to the LIM I test campaign reference is made to the contribution of Huybrechts & Legrand (1998).

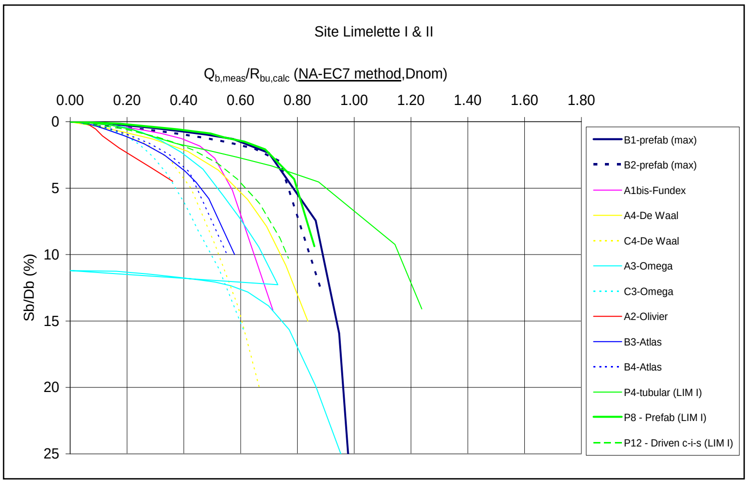


Figure 6 – normalised load settlement diagram of the pile bases in Limelette (LIM I & LIM II) (α_b = 0.7 for screw piles and α_b = 1 for driven piles have been applied)

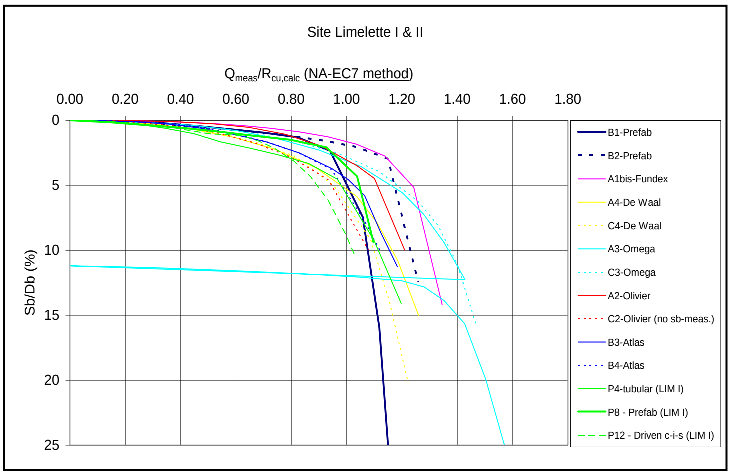


Figure 7 – normalised load settlement diagram of the piles' shaft friction in Limelette (LIM I & LIM II) (αs = 0.6 for tubular driven pile and αs = 1 for all other piles have been applied)

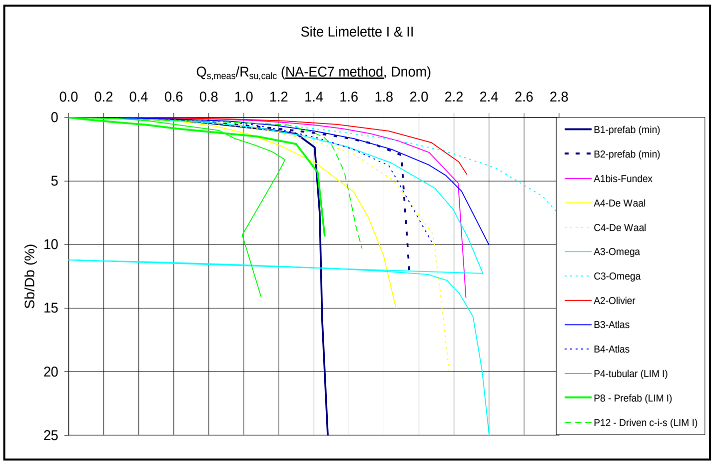


Figure 8 – normalised load settlement diagram of the total pile load in Limelette (LIM I & LIM II)

Based on the results presented in figures 6 to 8, one can conclude that:

- Corresponding to a settlement criterion of 10%Db, the calculated pile base resistances of the soil displacement screw piles seem too optimistic. It can also be deduced from figure 6 that pile the pile base resistance of soil displacement screw piles in this sand layer is fully mobilised at settlements of 25 to 30%D_b.

- For the driven piles, the calculated values seem to fit somewhat better to the measurements, but are still too optimistic. As mentioned before, residual stresses in the pile due to driving might partially explain this.
- From figure 7 it can be deduced that on the Limelette site the calculated values of the pile shaft resistances are far too pessimistic for all piles, in particular for the soil displacement screw piles

2.3 *Pile load test campaign in Loenhout*

Within the framework of the construction of the high speed railway in Loenhout, (Belgium), the BBRI was asked to perform scientific pile load tests on a soil displacement screw pile of the Omega type and on a CFA pile installed with casing. Details about these load tests have been reported by Theys et al. (2003).

Figure 9 illustrates the subsoil and the installation depths of one of the test piles. The following soil layers have been identified:

- Silt & clay to silty sand : 1.0 m to 3.5 m
- Sand : 3.5 m to 5.1 m
- Clay : 5.1 m to 6.3 m
- Silt : 6.3 m to 9.0 m
- Sand : 9.0 m - …

The pile bases were installed at a depth of 9.47 m for the Omega pile and 10.4 m for the CFA pile with casing.

The normalised load settlement diagrams, that have been established in the same way as the load test results of the previous test campaigns are given in figures 10 to 12.

The calculated values have been determined based on the CPT with electrical cone in the axis of each individual pile, and based on nominal pile dimensions as fixed in the recent design rules.

For the soil layers in Loenhout the following values from the recent guidance rules have been applied in the calculated values in figure 10 tot 12:

- α_b = 0.7 for the soil displacement screw piles and α_b = 0.5 for the CFA pile with casing
- $\varepsilon_b = \beta = \lambda = 1$ for all piles
- η_{pi}^* = 1/80 for the silt and clay to silty sand layers from 1.0 m to 3.5 m
- η_{pi}^* = 1/90 for the sand layer from 3.5 m to 5.1 m
- η_{pi}^* = 1/30 for the clay layer from 5.1 m to 6.3 m
- η_{pi}^* = 1/60 for the silt layer from 6.3 m to 9.0 m
- $q_{s,i}$ (MPa) = 0.110 + 0.004.(q_c-10) wit a maximum of 0.150 MPa for the sand layer from 9.0 m to pile base
- $\alpha_{s,i}$ = 1 for the soil displacement screw pile
- $\alpha_{s,i}$ = 0.5 for the CFA with casing

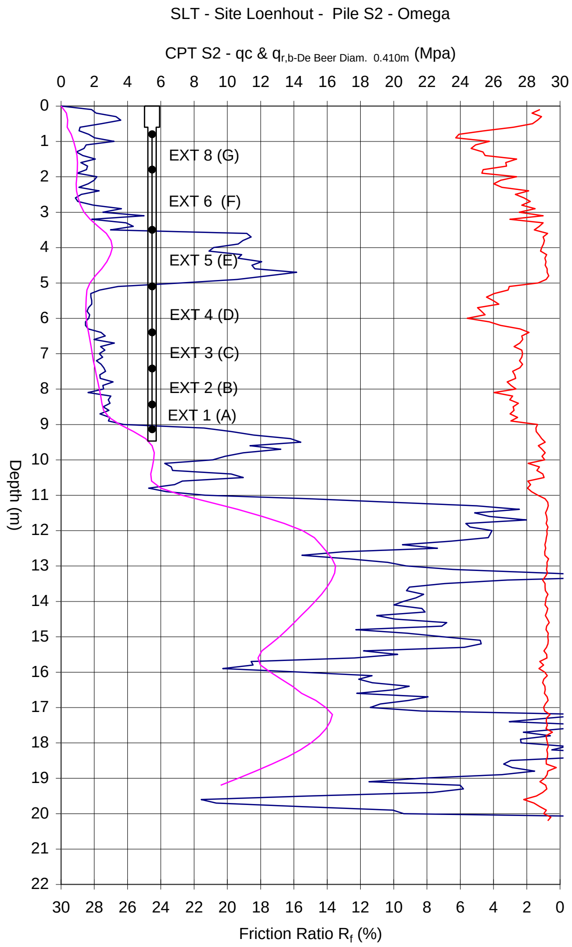


Figure 9 – CPT and pile depth Omega screw piles on the Loenhout site (B)

The measured values of the pile base resistance and shaft friction have been deduced from pile deformation measurements with a retrievable extensometer device, using the Fellenius (2001) interpretation methodology in order to deal with a non-linear stress-strain behaviour of concrete. Furthermore, as the test piles were excavated after the load tests, the real pile dimensions and the concrete quality with depth have been taken into account in this interpretation.

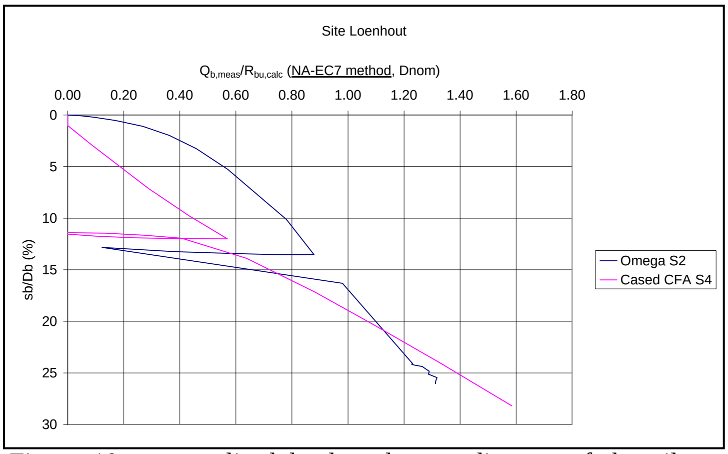


Figure 10 – normalised load settlement diagram of the pile bases in Loenhout (α_b = 0.7 for Ω screw pile and α_b = 0.5 for cased CFA have been applied)

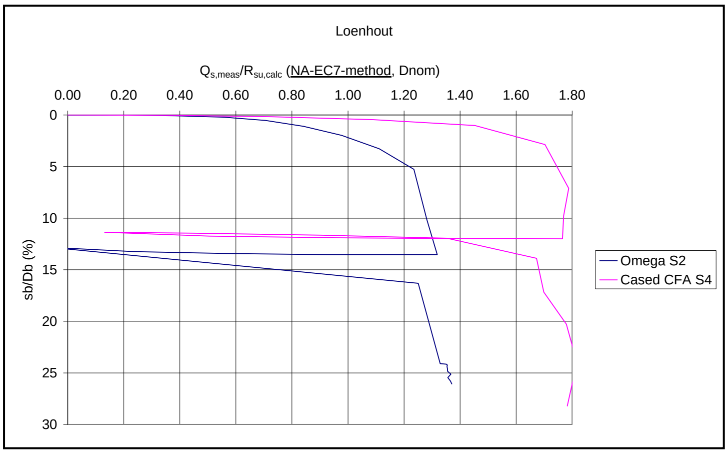


Figure 11 – normalised load settlement diagram of the piles' shaft friction in Loenhout ($\alpha_{s,i}$ = 1 for Ω screw pile and $\alpha_{s,i}$ = 0.5 for cased CFA have been applied)

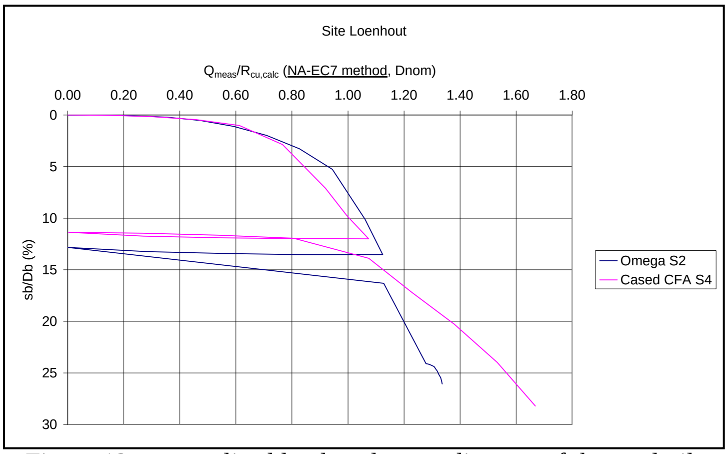


Figure 12 – normalised load settlement diagram of the total pile load in Loenhout

From figures 10 to 12 it can be concluded that

- the calculated value of the pile base resistance of the soil displacement screw pile is somewhat too optimistic at a settlement of 10%D_b. The calculated value is mobilised at a displacement of 15%D_b. At a settlement of 25%D_b the base resistance of this pile was fully mobilised.
- For the CFA pile the calculated base resistance is far too optimistic at a settlement of 10%D_b. From figure 10 it can be stated that the base resistance continues to increase with increasing displacement. From figure 10, it can also be observed that almost no pile base resistance is mobilised in the beginning of the load test, which indicates possibly soil relaxation beneath the pile point due to a pile execution problem. This has been confirmed in the contribution of Theys et al. (2003), more specifically by the results of CPT performed near the pile shaft after the load tests, and by the observations of the dimensions and shape of the excavated pile (see Figure 13).
- From figure 11 it can be deduced that the calculated shaft resistances is too pessimistic for both pile types, but in particular for the CFA pile with casing.

Figure 13 – Excavated CFA pile (left) with casing site Loenhout - detail of the pile base

2.4 *Pile load test campaign in Kallo*

In 1982 the Ministry of Public Works organised a load test campaign on two driven and two bored piles (performed with bentonite) on a site in Kallo (Kallo III). The tests were performed under the supervision of the former "National Pile Commission" and in collaboration with the UCL. Results of these test campaign were published in (BGGG, 1985), and by De Beer (1988).

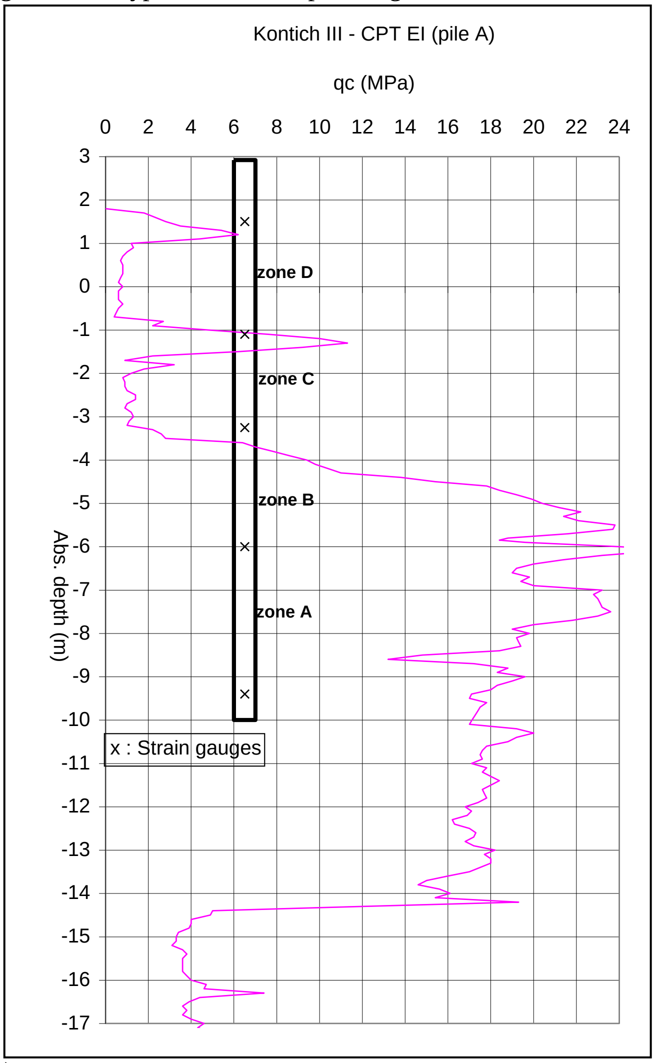
The analysis in this contribution has however been based on the detailed test reports of UCL (1987). The influence of residual pile loads on the interpretation of the measured load distribution of the driven piles as given by De Beer (1988), has been neglected in this contribution.

Figure 14 illustrates the subsoil and the installation depths of the test piles. The following soil layers have been identified:

- Quaternary sandy silt & clay layers: -0.80 m to -3.20 m
- Tertiary Sand : -3.20 m to -14.4 m

The pile bases were installed at a depth of -10.0 m

Figure 14 – Typical CPT and pile lengths on the Kallo III site



(B)

The normalised load settlement diagrams, that have been established in the same way as the load test results of the previous test campaigns are given in figures 15 to 17.

The calculated values have been determined based on the CPT with electrical cone in the direct neighbourhood of the piles (±1 m distance), and based on nominal pile dimensions as fixed in the recent design rules

For the soil layers in Kallo the following values from the recent guidance rules have been applied in the calculated values in figure 10 tot 12:

- α_b= 1 for the driven piles and α_b = 0.5 for the bored piles
- $\varepsilon_b = \beta = \lambda = 1$ for all piles
- $\eta_{pi}^* = 1/80$ for sandy silt & sandy clay layers: -0.80 m to -3.20 m
- $q_{s,i}$ (MPa) = 0.110 + 0.004.(q_c-10) with a maximum of 0.150 MPa for the sand layer from -3.20 m to pile base
- $\alpha_{s,i}$ = 0.6 for the driven tubular piles
- $\alpha_{s,i}$ = 0.5 for the bored piles

The measured values of the pile base resistance and shaft friction have been based on the values given in UCL (1987).

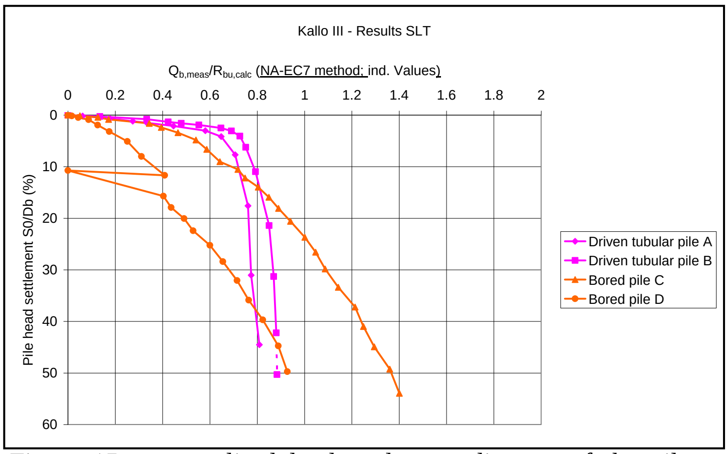


Figure 15 – normalised load settlement diagram of the pile bases in Kallo (α_b = 1 for driven piles and α_b = 0.5 for bored piles have been applied)

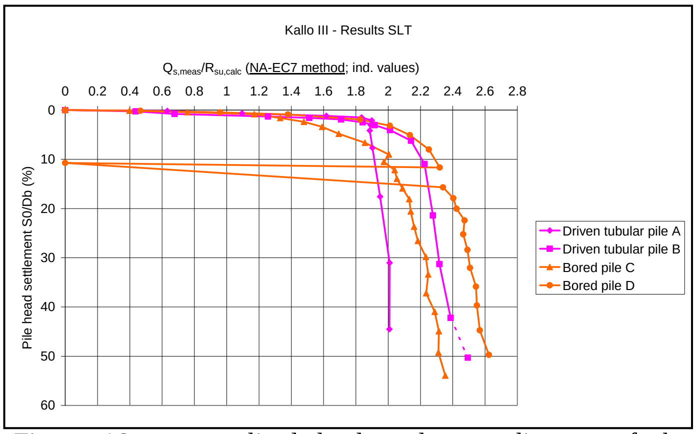


Figure 16 – normalised load settlement diagram of the piles'shaft friction in Kallo ($\alpha_{s,i}$ = 0.6 for driven tubular piles and $\alpha_{s,i}$ = 0.5 for bored piles have been applied)

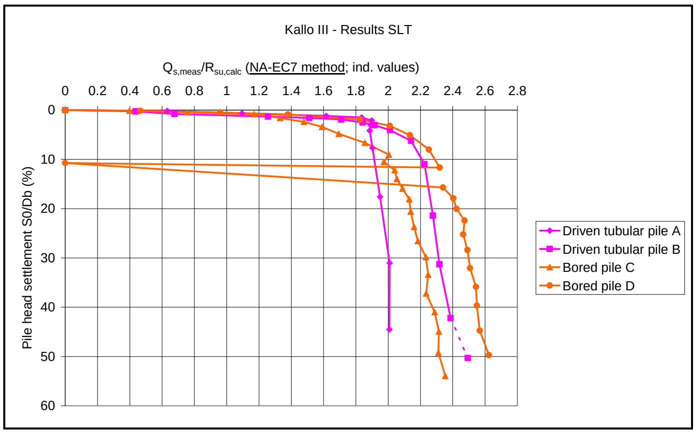


Figure 17 – normalised load settlement diagram of the total pile load in Kallo

Based on figures 15 to 17 one can conclude that

- For the bored piles the calculated base resistance is far too optimistic at a settlement of 10%D_b. From figure 15 it can be stated that the base resistance continues to increase even at very large pile displacements (up to 50%D_b)
- For the driven piles, the calculated values seem to fit somewhat better to the measurements, but are still too optimistic. As mentioned before, residual stresses in the pile due to driving might partially explain this.
- For both pile types, the calculated shaft friction is far too pessimistic.

3 CONCLUSIONS

Several instrumented pile load tests performed in Belgium by the BBRI since 1997, as well as some former load tests have been analysed. Pile base resistances and shaft friction deduced from these tests have been compared with calculated values following the recent design rules of piles in Belgium in BBRI (2008). In general it can be concluded that

- In tertiary clay a good correspondence seems to exist between calculated and measured values of pile base resistance and shaft friction for soil displacement screw piles and for precast driven piles. Recent tests on instrumented bored piles in tertiary Ypresian clay, which are not subject of this contribution, seem to confirm this for bored piles as well.
- With regard to the pile base resistance in sand, it can be stated that for driven piles the design rules seem to be somewhat optimistic, although the effect of residual stresses might explain this partially. For soil displacement screw piles the design rules are too optimistic corresponding with the settlement criteria of 10%D_b. The calculated base resistance seems rather to be mobilised at settlements of 15 to 25% D_b. For bored piles, the calculated values are far too optimistic at a settlement of 10%D_b and continue to mobilise pile base resistance until very large pile displacements.
- The calculated shaft friction in silt and sand seem to be too pessimistic for all piles, in particular for the soil displacement screw piles and the bored piles. This seems to compensate for the cases in the previous points were the prediction of the pile base resistance is too optimistic (at 10%D_b)
- More instrumented pile load tests of high quality on different pile types in different soil types are needed to assess in the future in a more accurate way the real load distribution along piles.

REFERENCES

BBRI, 1998-2000 & 2000-2002. Soil displacement screw piles – calibration of calculation methods and automatisation of the static load test procedure : stage 1 - friction piles & stage 2 – end-bearing piles. Research programs subsidised by the Belgian Federal Ministry of Economical Affairs, convention numbers CC-CIF-562 and CC-CI-756.

BBRI, 2008. Richtlijnen voor de toepassing van Eurocode 7 in België. Deel 1 : het grondmechanisch ontwerp in uiterste grenstoestand van axiaal op druk belaste funderingspalen / Directives pour l'application de l'Eurocode 7 en Belgique. Partie 1 : Dimensionnement géotechnique à l'état limite ultime de pieux sous charge axiale de compression. Document available in Dutch and French on www.tis-sft.wtcb.be and www.bggg-gbms.be (English version will be available by mid-2008)

BGGG-GBMS, 1985. Belgian Geotechnical Volume published for the 1985 Golden Jubilee of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE), by Belcotec and Belgian Member Society of ISSMFE. Brussels, 1985.

De Beer, E. 1971-1972. Méthodes de deduction de la capacité portante d'un pieu à partir des resultants des essays de penetration. Annales des Travaux Publics de Belgique, N° 4 (p191-268), 5 (p321-353), 6 (p351-405). Bruxelles)

De Beer, E. 1988. Different behaviour of bored and driven piles, proceedings of the Deep Foundations on Bored and Auger Piles Conference, Ghent, 1988

Fellenius, B.H. 2001 From strain measurement to load in an instrumented pile, Geotechnical News, March 2001.

Holeyman, A., Bauduin, C., Bottiau, M., Debacker, P., De Cock, F., Dupont, E., Hilde, J.L., Legrand, C., Huybrechts N., Mengé P., Simon G., 1997. Design of axially loaded piles – Belgian practice.
Proceedings of the ERTC3 seminar, Brussels.

Huybrechts, N. & Legrand, C. 1998. Static and dynamic pile loading tests on different types of driven piles in Limelette, DFI 98 Conference, Vienna.

Swets & Zeitlinger, 2001. Holeyman A. (ed.). Screw Piles : installation and design in stiff clay, Lisse (The Netherlands)

Swets & Zeitlinger, 2003. Maertens, J. & Huybrechts, N. (eds.). Belgian Screw Pile Technology : Design and Recent Developments, Lisse (The Netherlands)

Theys, F., Maertens J., & Maekelberg, W. 2003. Practical experience with screw piles used for the high-speed railway in Belgium, Proceedings of the 2nd symposium on screw piles, May 2003, Brussels

UCL - Laboratoire du Génie Civil, Etude du Pouvoir portant des pieux – Chantier de Kallo, Rapport des essais 265/1-84, Juin 1987