Prediction and verification of a precast concrete pile driven in Boom clay

Exercice de prédiction de capacité portante sur une mise en charge de pieux prefab dans l'argile de Boom

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ABSTRACT: A testing program was carried out on Precast concrete pile in Belgium in 1998-2000. This program included static, dynamic and statnamic load test on piles two different lengths. Within the framework of this project, an international prediction event was undertaken. This paper provides a description of prediction results, in terms of separation in end bearing and friction capacities, of total capacity and of stiffness. It also describes the use which one can make of the experimentation on piles two different lengths.

RÉSUMÉ: Un programme d'essai de mise en charge de pieux en béton (notamment préfabriqués) a été entrepris en Belgique entre 1998 et 2000. Ce programme comprenait des essais de mise en charge statique, dynamique et statnamic sur des pieux de deux longueurs différentes. Dans le cadre de ce projet, un exercice de prédiction international a été organisé. Cet article décrit les résultats de cet exercice illustrée par la séparation de la capacité portante totale du pieu en une partie liée à la base et une autre partie liée au frottement le long du pieu. La raideur du pieu est également commentée tout comme l'utilisation faite des deux longueurs de pieux dans le traitement des résultats.

1 INTRODUCTION

1.1 *Program - References – Location*

A national research project has been organized in Sint-Katelijne-Waver (Belgium) between 1998 and 2000 by the Belgian Building Research Institute (BBRI) in order to establish the performance of different types of cast-in-place soil displacement screw piles (Legrand, 2001). The program included the installation and testing of 30 test piles in the stiff fissured O.C. Tertiary Boom Clay (Huybrechts, 2001). Among those are 5 Precast piles.
These piles installed are two different lengths long (the short ones measure nearly 7.5 m and the long ones measure about 11.6 m). The reason for that will be explain at the end of this paper.
1 statnamic test and 2 dynamic tests took place within the first and second week of August 1999 (the statnamic was performed on a long one and the dynamic tests were performed on both pile lengths); 2 static pile tests were performed between September 2nd and October 12th 1999 (as the dynamic tests, the static tests were performed on both pile lengths).

1.2 *Overview of the Belgian design procedure*

Pile design methods generally accepted in Belgium are characterised by the semi-empirical, yet direct transformation of soil bearing parameters measured using in situ testing or sounding. Mostly used in Belgium are design methods based on the CPT test: the unit base resistance is obtained from a scaling procedure of the cone resistance diagram while the pile shaft friction is obtained from the CPT total friction, local friction, and/or cone resistance diagrams. The method is the De Beer one which has been validated and calibrated with a lot of tests for a long period.

Installation coefficients have been introduced to account for the installation and forms effects of each pile and soil type.

The ultimate base resistance is deduced from the ultimate unit pile base resistance issued from the CPT test (M4) modulated for scale effects using the De Beer Method. The ultimate shaft friction is based on the total side friction Q_{st} the cone resistance q_c; and/or the local unit side friction f_s also issued from the modified CPT test.

More details are available in Holeyman et al., 1997.

1.3 *Role of the Precast pile ?*

The complete program was undertaken to develop a better knowledge of the Belgian soil displacement screw piles. It was important to compare the results with a reference soil displacement pile. The driven Precast one pile was chosen as that reference.

Also the precise length, the section and the concrete quality are well known and all the conclusions can be deduced by the testing method.

1.4 *Installation*

The Prefabricated piles were driven with a diesel hammer and the blow count diagram of 5 Precast piles is shown in figure 1.

The driving quality was controlled with PDA measurements (strain gauges in the upper part of the pile which measure the acceleration and the force during the blows)

1.5 *Prediction*

A prediction event was organized with the hope to document the profession's ability to estimate these new piles behavior using standard geotechnical investigation means as well as dynamic testing (Holeyman et al., 2000a and 2000b). It was asked to :

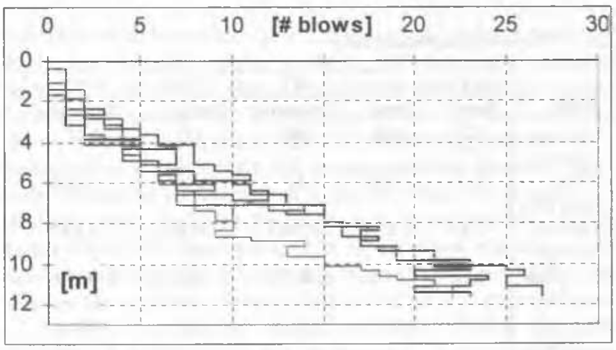

Figure1 : Blow count diagram of Precast Pile per 25 cm penetration.

- predict the load-bearing behavior of the piles based on the results of the dynamic pile load tests, and
- predict the static ultimate pile bearing capacity and the load-bearing behavior of the piles by means of the ground investigation results.

More information are available on this project in Holeyman et al, 1999a and 1999b.

2 PRESENTATION

2.1 *Test program*

2.1.1 *Static Load Test*

The ultimate capacity R_u of the pile was estimated by the BBRI and the experts from the National Steering Committee using De Beer's method based on the CPT tests results (De Beer, 1971-2). The load increment ΔQ was $R_u/8$. The ultimate capacity was considered reached when the pile head settlement was equal to 10% $\varnothing_{base}$. The SLT loading procedure is characterized by a pre-load stage, 10 maintained load steps (duration : 60 minutes) with equal ΔQ until R_u, a load perform until a pile head settlement $\geq$ 15% $\varnothing_{base}$ and an unloading in 4 steps of 10 min. each, except for final unloading (30 min at least of monitoring).

2.1.2 *Dynamic Load Test*

The loading device used to impact the piles dynamically was a 4 tons drop hammer operated by a crane, as illustrated on Figure 2. A sequence of several blows was applied to each pile. The drop height sequence most often applied was as follows: 0.4 m, 0.8 m, 1.2 m, 0.8 m, and 1.2 m.

Dynamic measurements of strain and acceleration were acquired for the piles using TNO FPDS5 and PDI PDA-PAK system. The transducers were attached generally 1.2 m from the top of the pile. Displacements were acquired using a laser system developed by DCI.

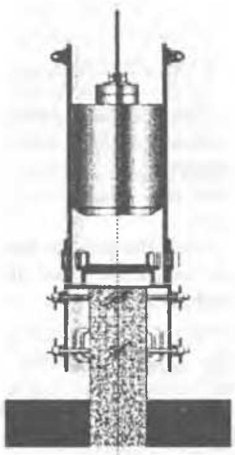

Figure 2 : Dynamic load device.

2.2 *Pile*

The Piles (installed on June, 6th 1999) are described as below: A square base (35x35 cm²), a nominal shaft diameter of 0.446 m, a nominal pile base diameter of 0.395 m and they are prefabricated with a B55 concrete (NEN 5950, 1995)

Table 1 : Pile in-situ characteristics.

	A1	A4	A7	A8	D2
TEST	Static	Static	Dynamic	Dynamic	Statnamic
Test age [days]	120	120	68	68	61
Total Length [m]	7.61	11.94	13	8	12.05
Pile Base depth [m]	-7.39	-11.58	-11.63	-7.44	-11.67
Excavation level [m]	-1.04	-0.98	-0.75	-0.71	-0.87
Top Level Pile Head [m]	+0.22	+0.36	+1.37	+0.56	+0.38

3 RECIEVED PREDICTIONS

3.1 *Reporting format and Predictions types*

The predictions are reported herein under an anonymous format in order not to stigmatize those with less accurate predictions. Each prediction is however labeled with a code corresponding to the prediction type.

Table 2 : Prediction types

"CPT"	predictors using the CPT results
"PMT"	predictors using the PMT results
"LAB"	predictors using the laboratory results
"DLT"	predictors using the Dynamic Load Test results
"STN"	predictors using the Statnamic Test results
"SLT"	Static Load Test

The CPT predictors used different methods, including ultimate state design as well as load transfer curves. All the contractors' predictions were made using CPT results and De Beer's 1974 method. The PMT predictors used the pressiometric approach that provides stress-displacement relationships for the shaft and the base. The LAB predictor used a load-transfer functions method based on plasticity indices.

The DLT predictors' methods included either CAPWAP or SIMBAT: the soil parameters in a model are adjusted to get the best match between the measured and the predicted signals of a Dynamic Load Test. SIMBAT is an empirical method converting the dynamic reaction to a static reaction.

The STN predictor used the Unloading Point Method (UPM) to predict the static load test. It was mentioned by the predictor that, due to strain rate sensitivity of clayey soils, a 30% reduction coefficient had to be applied on the usual UPM method. A hyperbolic approximation of that reduced function was then calculated. This is the reason why those predictions are reported herein as "0.7 STN".

4 RESULTS

4.1 *Ultimates Capacities for long and short piles*

Tables 3 and 4 show the results of the different components (when available) and the total ultimate capacities for each predictions.

Figures 3 and 4 show the load (Q) – settlement (s) predictive curves for short and long piles.

Figures 5 and 6 provide histograms of the pile capacity predictions, the friction capacity on one hand, and the end bearing capacity on the other hand. The short and the long results appear

Table 3 : Ultimate capacity components (for the A1 & A8 short piles).

Capacity [KN]	Friction (Qs)	End Bearing (Qb)	Total (Qt)
DLT1	*788*	*127*	*915*
DLT2	472	807	1279
DLT3	*797*	*399*	*1196*
DLT5	766	172	938
CPT1	515	263	778
CPT5	689	237	926
LAB	331	241	572
PMT1	388	141	529
PMT2	355	278	633
Mean 9 Predictions	567	296	863
COV	34%	70%	30%
SLT			*832*
CPT4			940
DLT4			1888
DLT6			1463

Table 4 : Ultimate capacity components (for the A4 & A7 long piles).

Capacity [KN]	Friction (Qs)	End Bearing (Qb)	Total (Qt)
DLT1	1501	127	1628
DLT2	1317	1065	2382
DLT3	1778	122	1900
DLT5	1403	189	1592
CPT1	1049	317	1366
CPT5	1324	294	1618
LAB	626	266	892
PMT1	741	178	919
PMT2	592	313	905
Mean 9 Predictions	1148	319	1467
COV	36%	91%	34%
SLT			1364
CPT4			1640
DLT4			2994
DLT6			1886
0.7 STN			2177

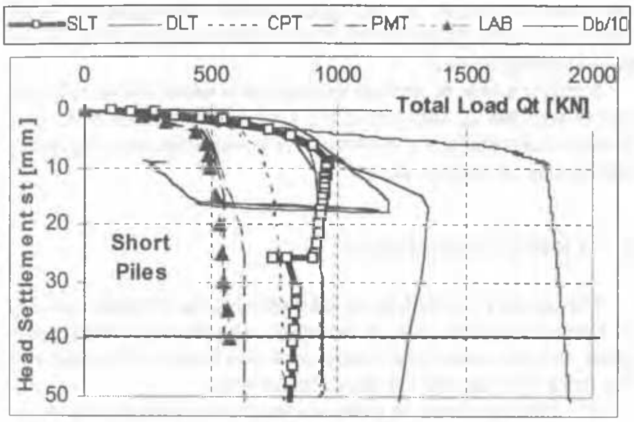

Figure 3 : Predictive Qt comparison of short piles

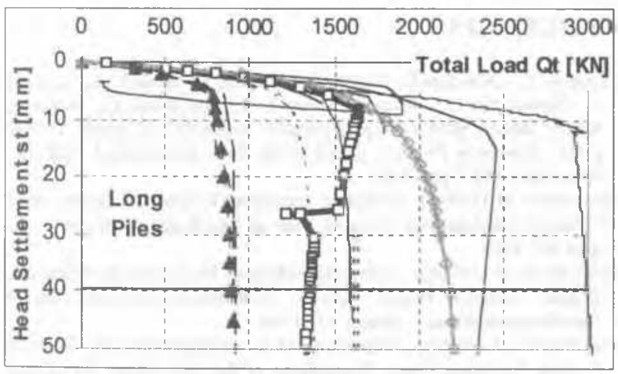

Figure 4 : Predictive Qt comparison of long piles.

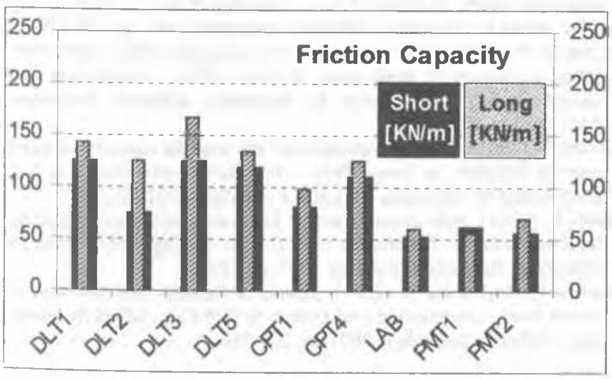

Figure 5 : Friction Capacity distribution for long and short Precast piles.

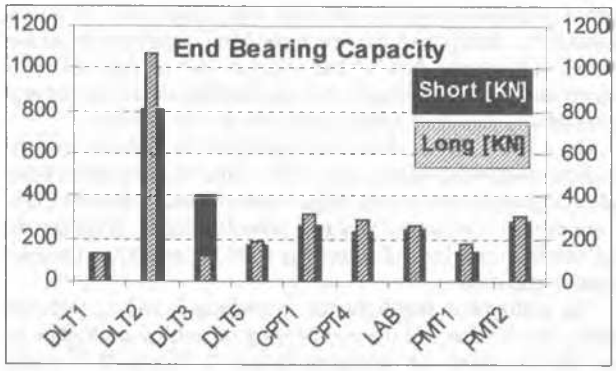

Figure 6 : End Bearing Capacity distribution for long and short Precast

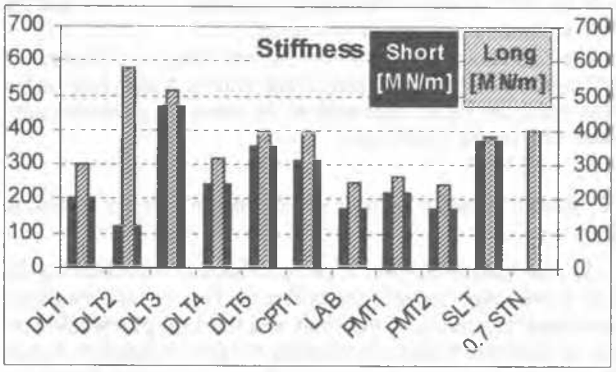

Figure 7 : Stiffness distribution for long and short piles.

on the same plot, the short ones in full columns and the long ones in stripped columns. The friction capacity plot displays the friction force per meter of pile in order to better compare both of lengths. The end bearing capacity is reported with force unit because of the same section for both of pile types.
Comparison with the measured friction and bearing capacities was not possible because interpretation of extensometers was not finalized at the time of preparing this paper.

4.2 *Stiffness components of short and long piles*

Figure 7 provides a similar histogram regarding stiffness components of the pile behaviour at a limited load, taken as 50% of the relevant ultimate bearing component (called k_t). Both pile lengths are shown on the same plot.

5 DISCUSSION OF PREDICTIONS AND RESULTS

5.1 *Distribution of prediction results*

The load-settlement curves (Figures 3 & 4) resulting from the static load tests (SLT) show a good proportionality between load and settlement up to 5 mm settlement. Beyond that point, the curves deviate from their initial linear trend. After a peak resistance, the pile settles under a slowly decreasing load beyond settlements exceeding 10 mm. All the predictions show a very similar trend compared with the first part of the SLT load-settlement curve. The peak resistance and the decreasing appear only on some dynamic predictions. All the geotechnical methods show a safe prediction (compared with the SLT) excepted some CPT methods which just give the ultimate value and which are nearly equal to the SLT peak value. The dynamic and statnamic methods overestimate the ultimate capacities, highlighting the discussion on the reduction from dynamic to static soil resistance.

The DLT2 prediction influence strongly all the histograms (Figure 5 & 6) because of his disproportional end bearing capacity. The removal of the DLT2 values of the statistical analysis induce a harmonization of the COV (the range [35 – 90%] becomes [28 – 40%]) and the new mean total capacities are closer by the SLT results than by the complete set of data (811 KN (short) and 1353 KN (long)). The end bearing capacities are also considerably modified (from about 300 KN to 230 KN).

The COV analysis allows to highlight the influence of the predictor judgment. Indeed, the COV of the bearing components taken separately are always higher than the total capacity COV. It emphasize that some "design" schools tend to privilege the end bearing capacity and others the friction capacity in the total capacity partition.

The histograms highlight the increasing f_s and q_c with the depth : the friction and the end bearing capacities are higher for long than for short pile (excepted for the DLT2 and DLT3 methods). The end bearing capacity predicted using Dynamic methods seems to be influenced by the difficulties to know how to reduce the soil resistance from dynamic to static. The CPT and the PMT methods are respectively similar.

The stiffness study shows on the one hand the influence of the length on the stiffness (increasing with the length) and on the other hand the better approach of the dynamic methods (compared with the SLT stiffness).

5.2 *Benefit gained from tests results on two different lengths of piles*

As discussed in Section 1, two pile lengths were used for the SLT. It was expected that the difference between the measured total bearing capacity of the short and the long pile would provide an alternate means of evaluating the pile installation factors for pile base and shaft assuming that the installation factors are identical for both the short and the long piles.

When the shaft friction is calculated from the total side friction ΔQ_{st} out of CPT-M1 and the end bearing from the q_c results of CPT E1 both transformed by De Beer's method , a set of two equations can be established :

$$Q_{u,S} = \alpha_b.\varepsilon_b.A_b.q_{bu}{}^{(m)}{}_S + \xi_f.(X_s/\pi d).\Delta Q_{st,S}$$

$$Q_{u,L} = \alpha_b.\varepsilon_b.A_b.q_{bu}{}^{(m)}{}_L + \xi_f.(X_s/\pi d).\Delta Q_{st,L}$$

With :

Q_u : the measured total bearing capacity of the short/long pile (conventional rupture load $(0.10D_b)$)

$q_{bu}{}^{(m)}$: the calculated ultimate unit pile base resistance.

ΔQ_{st} : the total side friction out of CPT-M1

A_b : the nominal pile base cross-sectional area

X_s : the nominal pile shaft parameter

d : the diameter of the sounding rod (3.6 cm)

ε_b, : a known installation factor = $1 - 0.01(D_b/d - 1)$

α_b, ξ_f : the unknown installation factors.

The subscribes "L" or "S" refer to the Long or Short pile, respectably.

More details are available in Maertens et al,2001.

It can be simplified by using global terms of end bearing and friction capacities (B_s, B_L, F_S and F_L). More, B_S can be expressed as a fraction of B_L ($B_S = k_B B_L$), also F_S and F_L (k_F) and $Q_{u,S}$ and $Q_{u,L}$ (k_Q). k_Q is the safest parameter because of its testing origin.

$$\begin{bmatrix} B_S & F_S \\ B_L & F_L \end{bmatrix} \begin{bmatrix} \alpha_b \\ \xi_f \end{bmatrix} = \begin{bmatrix} Q_{u,S} \\ Q_{u,L} \end{bmatrix} \Rightarrow \begin{bmatrix} B_S & F_L \cdot k_F \\ \frac{B_S}{k_B} & F_L \end{bmatrix} \cdot \begin{bmatrix} \alpha_b \\ \xi_f \end{bmatrix} = \begin{bmatrix} Q_{u,S} \\ \frac{Q_{u,S}}{k_Q} \end{bmatrix}$$

This system is illustrated in Figure 8.

The intersection of continuous lines represent the solution in terms of installation factors (α_b, ξ_f).

The sectors observed on Figure 8 represent the variability of k_B and k_F based on the analysis of the other piles in the general project. These variabilities influence strongly the solution of the system. k_B and k_F are directly influenced by the variability of the CPT data, spatially and mechanically (type of used cone). The firm methodology influence also the results.

Finally, the similarity of the angular coefficients also causes a great variation of the intersection's uncertainty. That's due to the weak evolution of the geotechnical characteristics with depth and to the preponderance of friction on end bearing in the total bearing capacity.

It also possible to analyze the two installation factors with the use of the only q_c data out of the CPT-E (integration of f_s (unit friction resistance) as a hyperbolic or power function of q_c) but it will appear in another paper.

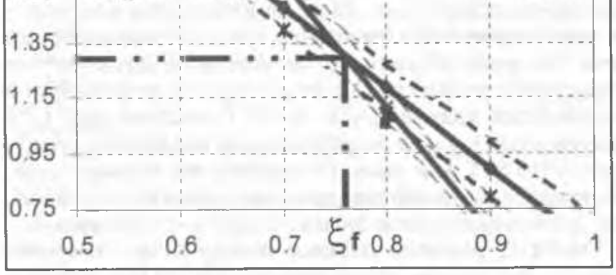

Figure 8 : System of equations with unknown installation factors

6 ACKNOWLEDGMENTS

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