INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Class A predictions on the basis of CPT of 10 instrumented screw piles in OC clay

Prédictions de niveau A sur base de CPT de 10 pieux vissés instrumentés dans une argile surconsolidée

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ABSTRACT: In 1999 an extensive research program on 30 piles, including driven precast piles and 5 screw pile types has been conducted in Belgium. Detailed in situ and laboratory soil investigation, static load tests up to failure, Statnamic and dynamic testing have been performed. The author participated at an international prediction event, its predictions being of class A for all screw piles tested. The predictions are mainly based on the CPT test results and hyperbolic transfer functions for base and shaft resistance. They were extremely accurate for the precast driven piles and the Fundex screw piles. For the other screw pile types, the ultimate resistance was generally overestimated by about 20%. The paper provides a description of the design methodologies and parameters applied to predict the ultimate base and shaft resistances and the stiffness factors defining the transfer functions. Predictions are critically compared with the measured load-displacements.

RÉSUMÉ: En 1999 une campagne étendue de recherche a été conduite en Belgique sur 30 pieux, de type battu préfabriqué et 5 types de pieux vissés. Une reconnaissance détaillée du sol in situ et en laboratoire, des essais de chargement statiques jusque rupture, des essais Statnamic et dynamiques ont été effectués. L'auteur a participé à un événement international de prédiction, ses prédictions étant de classe A pour tous pieux vissés. Les prédictions sont essentiellement basées sur les CPT et appliquent des fonctions de transfert hyperboliques pour la résistance à la base et au frottement. Elles étaient extrêmement précises pour les pieux préfabriqués et les Fundex vissés. Pour les autres pieux vissés, la résistance ultime était surestimée d'environ 20%. L'article fournit une description des méthodes et paramètres de calcul pour estimer la résistance à la base et au frottement, et des facteurs de rigidité définissants les fonctions de transfert. Les prédictions sont comparées aux courbes de chargement.

1 INTRODUCTION

A national research project has been organized by the Belgian Building Research Institute (BBRI) in order to establish the performance of different types of cast-in-place screw piles of the displacement type. All details on soil investigation, pile execution and pile testing are reported in a special volume (Holeyman-ed., 2001).

All in all six different types of ground displacement piles were installed (five of each) and tested statically (SLT), dynamically (DLT) or by Statnamic(STN): one prefab and five cast-in-place screw types including, Fundex, De Waal, Olivier, Omega and Atlas.. An extensive soil investigation was performed as part of the research project, including in situ tests (CPT, PMT, SPT, DMT, SASW) and laboratory tests on undisturbed samples.

On August 20th 1999, a reference document (Holeyman 1999a) comprising soil investigation data as well as the results of the dynamic and Statnamic pile testing was distributed internationally. Interested parties were invited to predict the load-bearing behavior of the piles. The author bravely took up the challenge to participate. On August 29th, complete information (Holeyman 1999b) on laboratory and in situ soil investigation and dynamic load test results was mailed to the predictors. The author's predictions were mailed to the organisers on September 5th, 2 days before SLT on the screw piles started.

2 SOIL PILE AND TESTING DATA

Typical CPT and PMT data are given in Figure 1 and 2 respectively. CPT-EB2 with electrical cone and CPT-MB12 and CPT-MB23 with mechanical M1 (Dutch cone) are located in the same area, close to pile B2 (long De Waal pile).

From each pile type, a serie of "short" piles, length approx. 7.5 m, and a "long" pile, length of about 11.5 m, was installed. Pile and test details are given in Holeyman (2001).

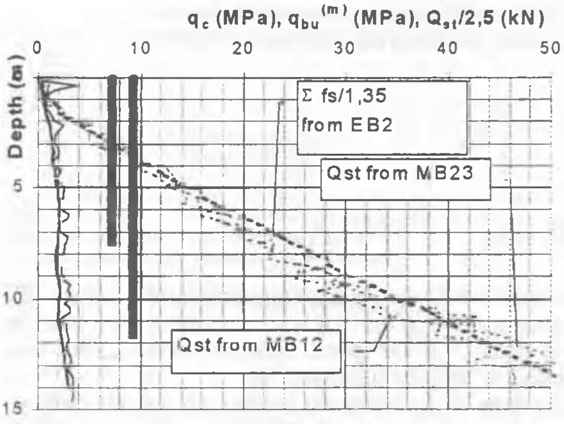


Figure 1. Typical CPT-data and deduced $q_{bu}^{(m)}$ value

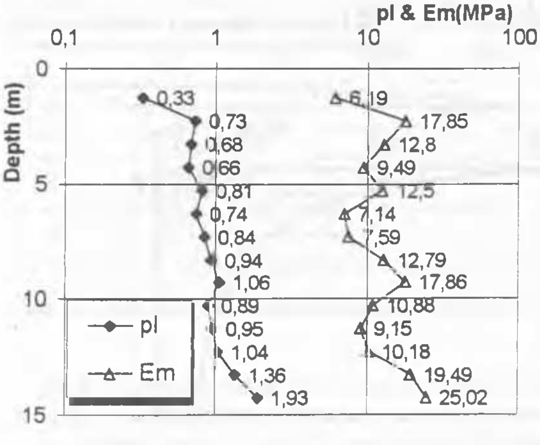


Figure 2. Data of Menard pressuremeter test PMT1

3 BASICS OF THE PREDICTION METHODOLOGY

3.1 *Deduction of ultimate resistances*

The ultimate base resistance R_{bu} and the ultimate shaft resistance R_{su}, both considered as the *conventional values* at a relative pile displacement $s=10\%D_b$ (D_b=pile base diameter) have been deduced from the CPT data. According to the Belgian methodology (Holeyman et al. 1997) one defines :

$$R_{bu} = \alpha_b . \varepsilon_b . q_{bu}^{(m)} . A_b \quad or = \alpha_{b,mean} . \varepsilon_b . q_{bu,mean} . A_b \tag{1}$$

with α_b an empirical (installation) factor taking into account the method of installation of the pile and the soil type;

$$R_{su} = \frac{X_s}{\pi d} . \xi_f . \Delta Q_{st} \text{ or } = \frac{X_s}{\pi d} . \sum \xi_{fi} . \Delta Q_{sti} \tag{2}$$

with ξ_f an overall empirical factor $(=\alpha_s . \beta_s . \varepsilon_s)$ introducing the effects of pile installation method (α_s), nature of the pile shaft material and roughness (β_s) and soil structure scale effects (ε_s).

$$R_{su} = X_s \sum H_i . \eta_{pi} . q_{ci} = X_s \sum H_i . \xi_{fi} . \eta_{pi}^{*} . q_{ci} \tag{3}$$

with η_p = an overall empirical factor depending on both soil and pile type. The correlation $\eta_p = q_c/q_{su}$ can be split into a pure soil parameter η_p^{*} equal to the ratio of q_c and the average unit side friction f_{su}, and a pile/soil dependent empirical factor ξ_f (as defined above).

3.2 *Transfer functions for R_b and R_s*

For the prediction of the load-displacement curves, the author applied hyperbolic transfer functions. The approach is based to a large extend on the significant work of Fleming (1992) amongst others on the validity of simple hyperbolic laws.

The transfer functions are expressed as follows:

$$R_b = \frac{s}{K_b + {}^{s}\!/_{R_{bu}}} \tag{4}$$

$$R_s = \frac{s}{K_s + {}^{s}\!/_{R_{su}}} \quad or \quad q_s = \frac{s}{K_s + {}^{s}\!/_{q_{su}}} \tag{5}$$

The base flexibility factor K_b (dimensions m/kN) corresponds to the tangent slope at the origin of the hyperbolic curve, as shown in figure 3. It also gives, multiplied with R_{bu}, the base displacement at 50% mobilisation of R_{bu}.

On the basis of the settlement formula for circular footings, K_b may be related to the secant modulus E_u (considered at 25% of the ultimate stress) by:

$$K_b = \frac{3.(1-\nu^2).f}{4D_b E_u} \approx \frac{0.54}{D_b E_u} \; with \; \nu = 0.4 \; and \; f = 0.85 \tag{6}$$

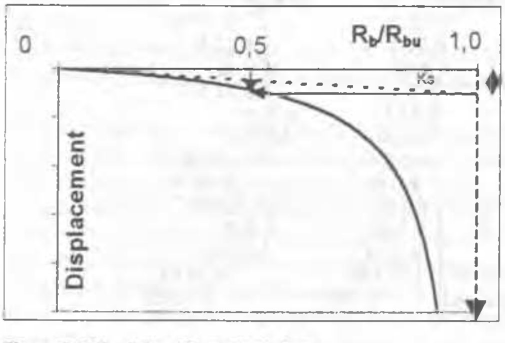


Figure 3. Principle of hyperbolic law

It should be emphasized in (6) that for the SLT, conducted in 1 hour load steps, the Young's modulus has been considered to be the *undrained modulus*.

From (6), one deduces the following relation between the base displacement at 50% of R_{bu} and K_b or E_u:

$$s_{50\%} = K_b . R_{bu} = \frac{0.212 D_b . q_{bu}}{E_u} \tag{7}$$

The shaft resistance flexibility factor K_s (dimensions m/kN) also corresponds to the tangent slope at the origin of a q_s-s diagram. With Fleming, one states that K_s is proportional to the pile's shaft diameter D_s and inversely proportional to the ultimate shaft friction R_{su} , and so:

$$K_s = \frac{M_s D_s}{R_{su}} \tag{8}$$

with M_s a dimensionless flexibility factor in the nature of an angular rotation.

4 APPLIED PARAMETERS IN THE PREDICTION

Contrary to the traditional Belgian methodology as applied by BBRI, the unit end bearing resistance in the natural ground conditions has *not* been calculated using the De Beer method (Van Impe 1988) which gives $q_{bu}^{(m)}$, but as the mean value of q_c over a depth of $2D_b$ below the pile base (indicated in Formula 1 by $q_{b,mean}$). Comparison of both values for the various CPT performed in the test pile axis, is given in Figure 4. The De Beer method, which smoothes the q_c-diagram, gives on average 15 % lower values than this mean q_c. The $q_{bu}^{(m)}$ value also may be over-influenced by only one local drop in the q_c value, as can be seen in Figure 1 for the low value at 11.0 m depth and therefor may not be realistic if not interpreted by sound engineering judgment. One notices that, in spite of the said homogeneity of the considered oligocene clay layer, the dispersion of the results over the various CPT is not negligible.

The ε_b factor refers to the scale dependent soil shear strength of the fissured clay. It has been deduced from previous research in the considered clay layer to be related to the ratio of the pile diameter D_b to the CPT cone diameter d by :

$$0.476 \leq \varepsilon_b \approx 1 - 0.01(D_b/d - 1) \tag{9}$$

In the initial prediction, the *pile base area* A_b has been calculated from 1.0 × the external diameter of the auger for Fundex, De Waal and Omega, and from 0.9 × the maximum auger flange diameter for Olivier and Atlas. For clarity, however, in this paper all factors are put = 1.0, incorporating the section reduction factor of 0.9^2=0.81 for Olivier and Atlas in the α_b factor. For $X_s = \pi D_s$, the maximum shaft diameters have been considered for all piles.

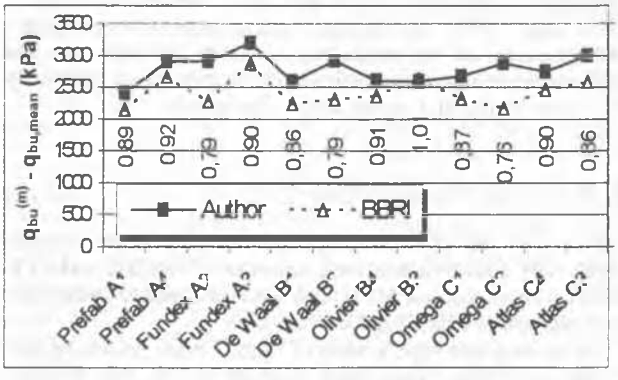


Figure 4. Unit end bearing (without installation factors) from CPT

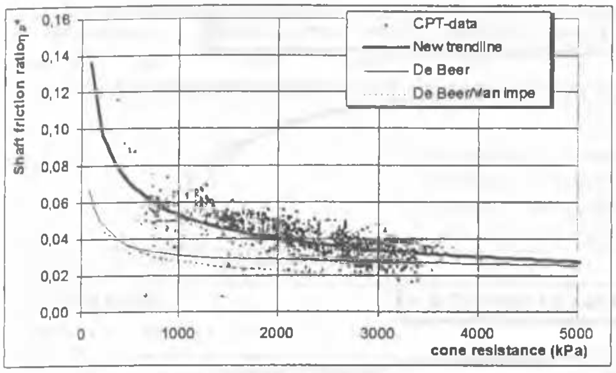


Figure 5a. Shaft friction ratio η_p* as a function of q_c

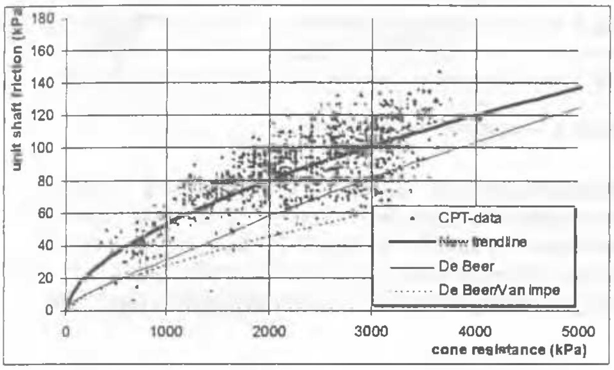


Figure 5b. Unit shaft friction $f_{s,red}$ as a function of q_c

The $\alpha_{b,mean}$ factor had been taken = 1.0 for all pile types (but so has now been replaced by 0.81 for Olivier and Atlas).

For ξ_f, the following values have been used in the prediction: precast piles 0.85, Fundex piles 0.80, De Waal and Omega 1.0, Olivier and Atlas 1.25.

The correlation factor η_{pi}* has been defined in 2 steps:

- 1st: the measured local friction values f_s from the electrical cone CPT have been reduced by a factor of 1.35 in order to obtain a good correlation between this reduced integrated local friction $f_{s,red}$ and the total rod friction Q_{st} with the mechanical cones; (see Figure 1);
- 2nd: the relation between $f_{s,red}$ and q_c.has statistically be analyzed. Figures 5a and 5b give the collection of the data points, the deduced trendline, as well as the relations earlier suggested by De Beer (1985) and Van Impe (1988).

From this, one deduces the following trendlines:

$$\eta_p{}^* = 0.9.q_c{}^{-0.41} \quad or \quad f_{s,red} = 0.9.\ q_c{}^{0.59} \qquad (10a)\,(10b)$$

For the calculation of K_b and K_s, the following values have been adopted:

- E_u = 175 to 225 MPa (≅1000 c_u or ≅70 q_c)
- M_s = 0.0015 up to 5 m depth and = 0.001 for $z>5$ m.

The E-modulus of the pile's concrete has been taken equal to 30 MPa, which has appeared later on to be smaller than the values of 35 to 40 MPa deduced from compression tests on concrete samples.

5 COMPARISON OF PREDICTIONS WITH SLT-CURVES

Figure 6 gives for all 6 pile types the comparative charts of the SLT curve ($Q_{t,meas}$) as well as the predicted curves for mobilised base, shaft and total resistance $Q_{b,pred}$, $Q_{s,pred}$ and $Q_{t,pred}$ respectivily, all expressed as a function of the pile head displacement s_t. Only data for the long piles are given. However the same conclusions apply to the short piles.

With regard to the measured load-curves, the attention is drawn on the following:

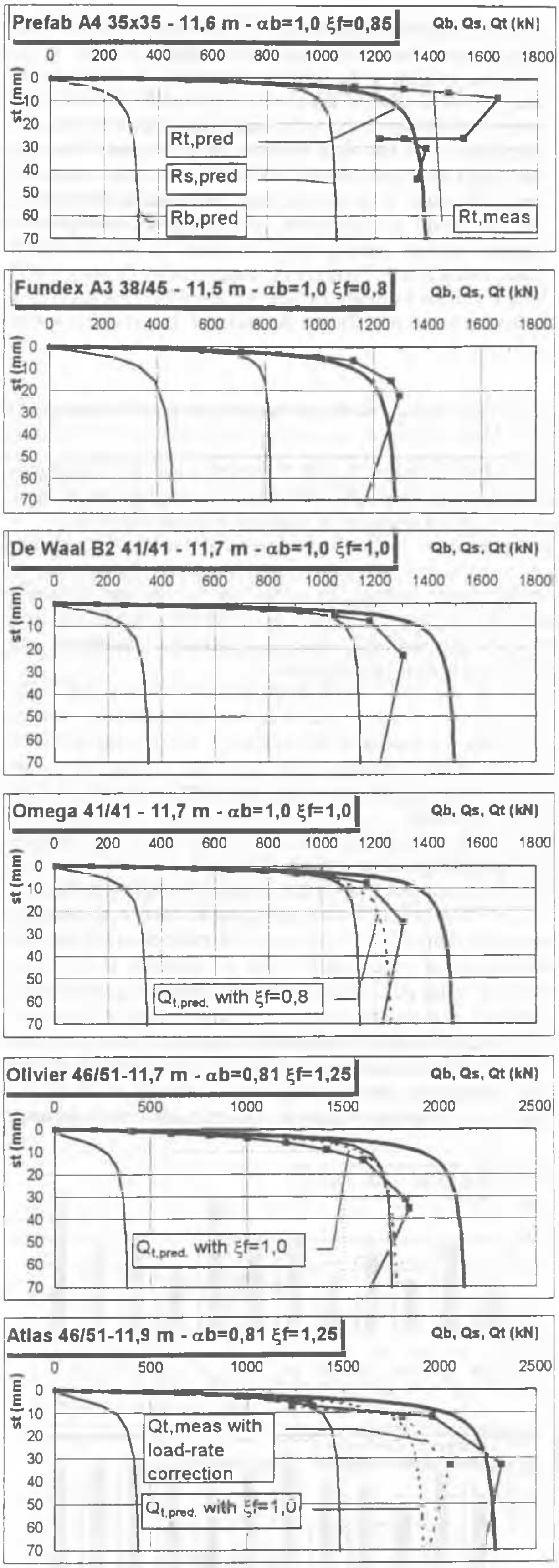


Figure 6. Comparison of predicted and measured pile behavior

- SLT were performed in 10 to 12 maintained load steps of 60'
- After reaching a peak resistance, piles were further displaced at constant rate of 0.6 to 0.8 mm/min; in all cases the load

therefor required decreased more or less significantly to what often is pretended to be the residual resistance.

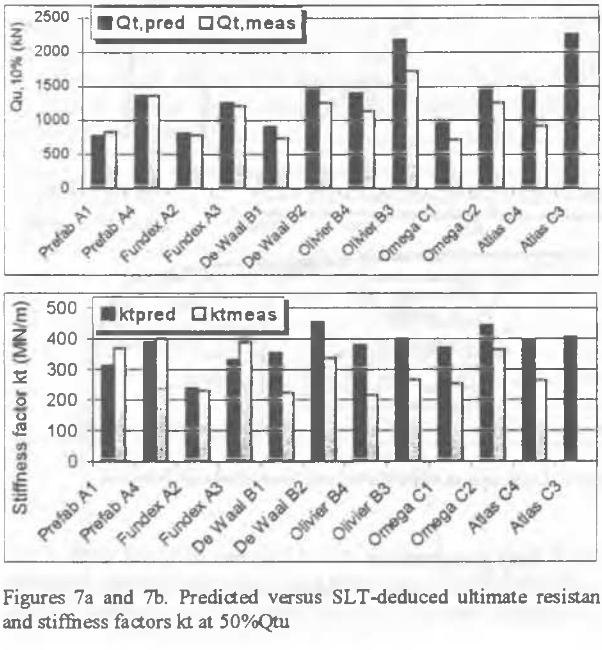
- Due to a problem in the pressure regulation of the hydraulic jack, the Atlas pile C3 was loaded very rapidly (50 mm/min) from 1300 kN up to 2315 kN peak value and 150 mm displacement. The test was restarted in a 2nd and 3rd cycle, reaching a new peak value of 1736 kN and displacements of about 220 mm!. It is obvious that the representativiness of the test should be questioned. The author has attempted to correct the first loading cycle by using the rate-dependent shear strength law (Formula 11) suggested by Briaud (1985) with a viscous exponent n=0.06 for Ip=40%. This leads to a reduction factor of 1.28 and the reduced SLT curve as given in Figure 6.

$$\frac{Q_{t1}}{Q_{t2}}=\left(\frac{t2}{t1}\right)^{n} \text{ with } Q_{t1} = \text{ultimate capacity reached in time } t1 \quad (11)$$

The charts in Figures 7a and 7b give information on both predicted and test-deduced pile resistances, as well as on stiffness factors (at 50% of predicted or deduced ultimate resistance).

Comparison of predicted and measured data leads to the following conclusions and remarks (unfortunately, the outcome of the extensometer analysis has at this time not yet been officially released by the research organizing committee, and so the individual base and shaft resistance mobilization as measured and predicted can not yet be evaluated).

- All in all, the shape of the predicted curve corresponds fairly well with the observed load-displacement behavior, considering that the measured displacements at high load levels as well as the peak resistance are very much influenced by the short duration of the load steps and therefor should be handled with caution.
- For prefab and Fundex piles, the prediction of the ultimate total pile resistance as well as of the total stiffness factor (see also the zoomed chart in Figure 8a) may be called perfect.
- For all other piles, the ultimate pile resistance is overestimated by about 15-25 % (what in soil mechanics still may be appreciated as "fairly well"), with a maximum of 50 % for the short Atlas pile C4. According to Formula 8, an overestimation of Rsu also results in an underestimation of the flexibility factor K_s and consequently to an overestimation of the inverse stiffness factors. By reducing the installation factors (but maintaining the same E_u and M_s factors) to fit $Q_{tu,pred}$ with $Q_{tu,meas}$, one also observes an excellent correspondance between the stiffness factors, as can be seen from Figure 8b. This seems to confirm the validity of the assumed flexibility parameters, as outlined in chapter 4. Further work on the deduction of the flexibility factors from soil parameters and soil tests, in particular from CPT, will be published in short time.



Figures 7a and 7b. Predicted versus SLT-deduced ultimate resistances and stiffness factors kt at 50%Qtu

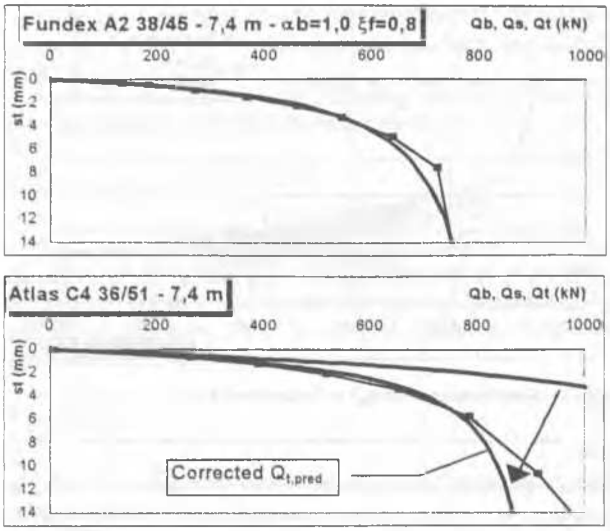


Figure 8. Comparison of pile stiffness

6 CONCLUSIONS

Hyperbolic transfer functions for pile end and shaft resistance do correspond very well with the overall pile-displacement curvature. The author however wants to make a reservation in case the base layer is subjected not only to displacement but also to substantial compressive (settlement) deformation. The predicted ultimate resistances were excellent for prefab and Fundex piles, but somewhat to optimistic in the estimation of the installation factors for De Waal, Omega, Olivier and Atlas piles. The applied stiffness factors have proven their validity, considering the dependence of the shaft resistance stiffness on the ultimate value and thus also on the relevance of the shaft installation factor.

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