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# Pile settlement under vertical static load : SLS design method based on Belgian experience

## Tassement des pieux : Dimensionnement à l'ELS sur base de l'expérience Belge

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ABSTRACT: Besides the verification of the Ultimate Limit State (ULS) of pile foundations, Eurocode 7 imposes a Serviceability Limit State (SLS) verification. A first method is presented in this paper using transfer functions to describe the nonlinear shaft and base pile reactions. Since it is commonly agreed that the prediction of pile performance is only as good as the input parameters, the outlined settlement parameters are based on back-calculation analysis of a large database involving more than 100 fully instrumented pile load tests .Integrated in a straightforward one dimensional (1D) Finite Element Method (FEM), the method shows a very good agreement with static load tests (SLTs) and has been elaborated in line with the current pile design practice in Belgium according to Eurocode 7. Also, a simplified second method, which allows a pile settlement prediction without numerical calculations, has been developed. It exists out of typical curves for pile settlement based, as well, on the aforementioned experimental database. Subject to some limitations, these typical curves give similar results as the numerical method (using transfer functions) for common pile types and pile lengths. Both methodologies provide useful instruments for SLS pile design in Belgium.

RÉSUMÉ : Outre la vérification des pieux à l'Etat Limite Ultime (ELU), l'Eurocode 7 impose une vérification à l'Etat Limite de Service (ELS). Une première méthode utilisant les fonctions de transfert est présentée dans cet article pour décrire le comportement non-linéaire des réactions au fût et à la base du pieu. Comme la prédiction du comportement des pieux doit se reposer sur une bonne estimation des paramètres, ces derniers sont basés sur une analyse inverse d'une large base de données de plus 100 essais statiques de pieux instrumentés. Cette méthode, intégrée dans un simple programme unidimensionnel (1D) en éléments finis, montre une bonne correspondance avec les essais de mise en charge statiques (SLTs) et en accord avec la pratique Belge pour le dimensionnement des pieux selon l'EC 7. De plus, une deuxième méthode plus simple permettant l'estimation du tassement du pieu sans devoir passer par un outil numérique a été élaborée. Elle consiste en l'élaboration de courbe-types de tassement de pieux qui sont basées sur la même base de données. Malgré ses limites, les courbes types donnent des résultats similaires à ceux obtenus par les fonctions de transfert pour des types et longueurs de pieux typiques. Les deux méthodes offrent des outils pratiques pour le dimensionnement ELS des pieux en Belgique.

KEYWORDS: vertically loaded pile foundations, SLS design, transfer functions, Belgian experience.

## 1 INTRODUCTION.

The European standard NBN EN 1997-1 "Eurocodes 7 : Geotechnical design – Part 1 : General rules" was published in Belgium in 2005 and has created a general common European framework for the design of geotechnical constructions. The Belgian National Annex (ANB) was published in 2014 and gives complementary information among others, the design approach, the design methods, the design factors and the safety factors. Due to the absence of geotechnical standards in Belgium in the past and due to the emergence of newly introduced techniques on the Belgian market, considerable research efforts were made during the last years to develop a scientific base for a uniform implementation of the EC 7 in Belgium. Aside from the Ultimate Limit State (ULS) design, EC 7 imposes a Serviceability Limit State (SLS) control. There are, however, no concrete rules related to SLS design in the Eurocodes.

SLS design consists, for pile foundations, to check if the pile settlement during all phases of the project is acceptable for the new construction. In practice, an indirect method based on limiting the mobilization of the bearing resistance is used with an overall safety factor (generally greater than 2 to 3). This stipulates that ULS verifications may cover SLS design. It is, however, appropriate to verify that the designed pile capacity does not endanger the serviceability of the structure. This may occur for example when the mobilized pile resistance occurs at large displacements or in the case of sensitive structures to displacement. BBRI studies were conducted in this context to fill the gaps regarding SLS design in Belgium. This article aims to provide a better insight for the SLS design of vertically loaded individual piles.

## 2 AVAILABLE METHODS FOR THE DETERMINATION OF INDIVIDUAL PILES

### 2.1 *Winkler approach (transfer function)*

Methods based on transfer function are the most used methods for estimating the pile displacement. It is inspired from the so-called Winkler approach where the soil is replaced by a series of independent nonlinear springs. Figure 1 illustrates the principle of the Winkler approach. Due to an axial load at the pile head, the soil will react along the pile shaft and at the pile base. These reactions are simulated in this approach as nonlinear springs, each one has its own reaction curve. In the literature, the terminology 't-z' and 'q-z' curves is used and is respectively related to the shaft and the base reaction. The differential equation of motion along the pile shaft is expressed as:

$$\frac{d^2z}{dx^2} - \frac{\chi}{E_pA_p}t = 0 \tag{1}$$

with $z$ [m] the pile displacement at depth x [m], $\chi$ [m] the pile shaft perimeter, $E_p$ [kPa] the pile Young modulus, $A_p$ [m²] the pile cross section and t [kPa] the mobilized friction at depth x and for a displacement z.

The differential equation of motion at the pile base is expressed as:

$$\frac{dz_b}{dx} - \frac{qA_b}{E_pA_b} = 0 \tag{2}$$

with q [kPa] the pile base reaction, $z_b$ the pile base settlement and $A_b$ the pile base section.

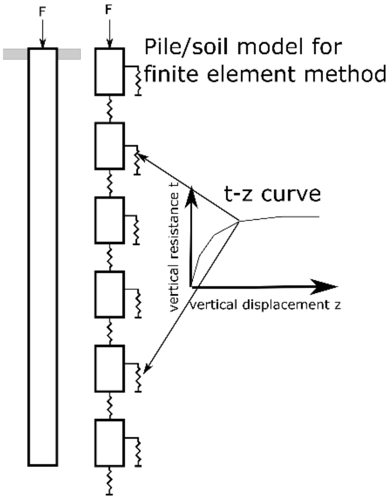

Figure 1. Illustration of the Winkler approach: modelling the soil with a series of independent springs ((Tomlinson & Woodward, 2007))

Several expressions of t-z and q-z curves exist in the literature: (API, 2002), (Gwizdala & Tejchman, 1993), (O'Neil & Reese, 1999), etc. Most of the transfer functions are independent of the soil type (sands or clays for example) and of the pile type. Intrinsic ground parameters such as the undrained cohesion or the internal friction angle are used for the setup of such functions. Correlations between these curves and the results of in-situ soil investigation such as CPTs are, on the other hand, less available in the literature.

Soil reactions at a given pile displacement are typically nonlinear. Many mathematical functions could be applied to represent the nonlinearity (power function, exponential function or hyperbolic functions). Previous works such as (Chin, 1970), (Chin & Vail, 1973), (Caputo & Viggiani, 1984), (Fleming, 1992) (1992) and (De Cock, 2008) recommended power or hyperbolic functions. These functions help to find the best fit with results of static pile loading tests (SLTs) through a back-calculation analysis. Based on the literature review, hyperbolic functions are elaborated in this study to represent the settlement behavior of most common pile and ground types present in Belgium. The elaboration of these functions is based on a large database of instrumented Static Loading Tests (SLTs) on piles.

### 2.2 *Typical curves*

Transfer functions are theoretical tools that should be implemented in a numerical program in order to obtain the predicted settlement of the pile under a given working load. The typical-curves method provides a rather pragmatic method that allows a quick graphical estimation of the predicted settlement. The method is inspired from the Dutch-approach cited in the (NEN 9997-1 +C1, 2012) which suggests the use of normalized load displacement diagrams for different types of piles. Similarly, typical curves proposed in this study are based on a large database available at BBRI for instrumented SLTs conducted in Belgium.

## 3 COLLECT AND TREATMENT OF AVAILABLE CASES

First, a large overview has been made of available SLTs performed in Belgium in the period [1970-1996] (A. Holeyman et al., 1997) and more recent in the period [1997 – 2015] (Maertens & Huybrechts, 2003) and (Huybrechts et al., 2016). In total more than 100 SLTs are analyzed. The following measurements are available for each analyzed SLT :

- The applied load at the pile head and the pile head displacement in function of the time
- The creep curve at each load step
- The deduced normal forces in function of the pile depth
- The load displacement curve divided into a pile shaft and base resistances
- The unit shaft resistance at each representative layer

Second, a selection of SLTs is elaborated in function of the following criteria: the general quality of the test, the applied instrumentation (at the pile head, optical fibers…), the ground type etc. Finally, data have been grouped based on the pile type. Piles were classified into three categories: driven piles, screw piles and replacement piles (continuous flight auger piles 'CFA' and bored piles). Similarly soils were sorted into three types: sands, clays and mixed soils. Mixed soils include silts, silty or clayey sands and silty or sandy clays.

## 4 ELABORATION OF HYPERBOLIC TRANSFER FUNCTIONS

### 4.1 *Back-calculation*

As the pile undergoes a displacement (z at the pile shaft and $z_b$ at the pile base), the transfer functions have, respectively, the following form for the reaction at the pile shaft t [kPa] and at the pile base q [kPa],:

$$t = \frac{z}{\frac{1}{k_{si}} + \frac{z}{t_{max}}} \tag{3}$$

$$q = \frac{z_b}{\frac{1}{k_b} + \frac{z_b}{q_{max}}} \tag{4}$$

where $t_{max}$ [kPa] is the maximum shaft resistance, $k_{si}$ [kN/m³] is the stiffness of the soil along the shaft layer i, $q_{max}$ [kPa] is the maximum pile base resistance and $k_b$ [kN/m³] is the stiffness of the soil at the pile base.

Eq. 3 and 4 may be rewritten as follows:

$$\frac{z}{t} = a_1 + a_2 z \tag{5}$$

$$\frac{z_b}{q} = b_1 + b_2 z_b \tag{6}$$

where $a_1 = 1/k_{si}$ , $b_1 = 1/k_b$ , $a_2 = 1/t_{max}$ and $b_2 = 1/q_{max}$.

Starting from Eq. 5 and 6, constants $t_{max}$ and $k_{si}$ for the pile shaft reaction could be back-calculated by fitting the experimental t-z curves obtained from SLTs (as illustrated in the example of Figure 2). Similarly, constants $q_{max}$ and $k_b$ for the pile base reaction could be deduced from q-z curves obtained in SLTs. The same back-calculation analysis was applied on all series of SLTs in different piles and soils. Then, back-analysed data were submitted to a parametric analysis to establish nondimensional reaction curves. The loading (at the pile shaft as well as at the pile base) is expressed as a ratio of the maximum resistance. Similarly, pile displacement is expressed as a ratio of the pile shaft/base diameter.

According to several authors (Fleming, 1992), (De Cock, 2008), etc…, there is a relation between the stiffness parameter $k_{si}$ and the dimensionless flexibility factor $M_s$ of the pile shaft:

$$M_s = \frac{t_{max}}{k_{si} d} \tag{7}$$

with d the pile shaft diameter.

In this way $k_{si}$ could be deduced as a function of the maximum resistance $t_{max}$. According to (Fleming, 1992) and (Castelli &

Maugeri, 2002), values of $M_s$ are generally in the range between 0.005 and 0.0005 ($M_s$= 0.0045 for weak soils and $M_s$ = 0.0005 for rather hard soils). By inserting $M_s$ factor into the hyperbolic function, a dimensionless equation is obtained. Figure 3a gives such reaction curves for different values of $M_s$

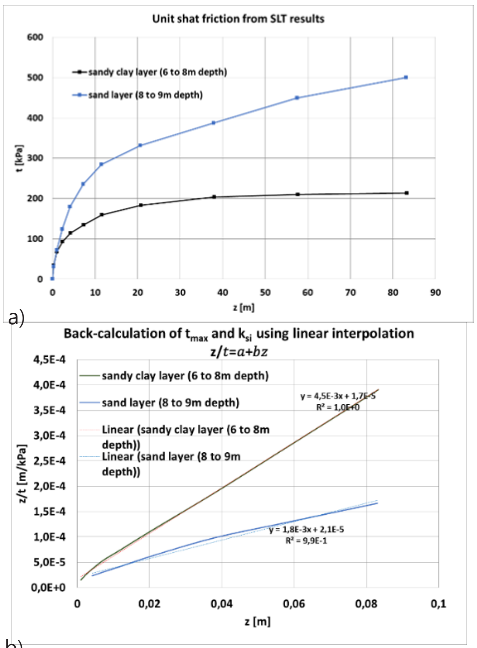

Figure 2. SLT results on pile C4 installed in Limelette (Maertens & Huybrechts, 2003): a) unit shaft resistance obtained from SLT for different layers and b) back-calculation of $t_{max}$ and $k_{si}$.

A dimensionless expression for the reaction at the pile base is more complex to establish. (Fleming, 1992) used the elastic theory of (Boussinesq, 2008) for the settlement of a circular spread foundation:

$$z_b = \frac{\pi q d_b (1-\upsilon^2)}{4E_b} f_1 \tag{8}$$

with $E_b$ [kPa] : the elastic modulus of the soil below the pile base, $\upsilon$ : Poisson coefficient, $d_b$: the pile base diameter and $f_1$ : influence factor.

The elastic modulus of the soil at the pile base $E_b$ is considered at a loading equal q to 25% of the maximum resistance $q_{max}$. The relation between $k_b$ and $E_b$ is then obtained by putting the Boussinesq equation (Eq. 8 with $\upsilon$=0.3 and $f_1$=0.85 for circular loading) equal to the hyperbolic function (Eq. 4):

$$k_b = \frac{E_b}{\beta} \tag{9}$$

with

$$\beta \approx \frac{0.58 A_b}{d_b} \approx 0.145\pi d_b \approx 0.455 d_b \tag{10}$$

Figure 3b gives the normalized curves for the pile base reaction with different range of the factor $M_b$ ($M_b$=10 in case of weak soils and. $M_b$=100 in case if hard soils) with:

$$M_b = \frac{E_b}{q_{max}} \tag{11}$$

By confronting this methodology with the large database of SLTs in Belgium, the dimensionless factors $M_s$ and $M_b$, which are given in Table 1 and Table 2 in function of the pile and the soil type, can be deduced.

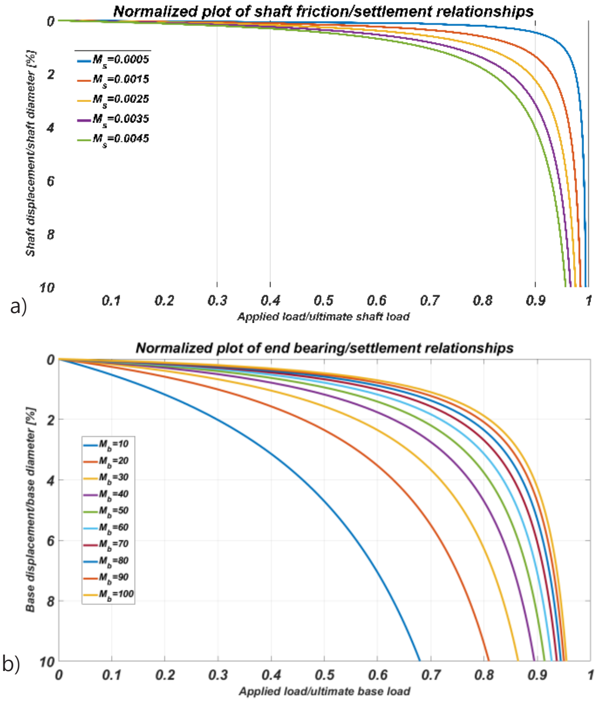

Figure 3: Normalized reaction curves for the pile a) shaft and b) base

Table 1. Dimensionless flexibility factors $M_s$ as a function of pile and soil types

| Pile type / Soil type | Driven piles | Screw piles | Replacement piles |
|---|---|---|---|
| Sands | 7.10$^{-3}$ up to 11.10$^{-3}$* | 7. 10$^{-3}$ up to 11.10-3 | 17. 10$^{-3}$ up to 26. 10$^{-3}$ |
| Mixed | 2.10$^{-3}$ up to 6. 10$^{-3}$ | 3. 10$^{-3}$ up to 6. 10$^{-3}$ | 6. 10$^{-3}$ up to 12. 10$^{-3}$ |
| Clays | 1.10$^{-3}$ up to 2. 10$^{-3}$* | 2.10-3 up to 4.10-3 | 3.10$^{-3}$ up to 4. 10$^{-3}$* |

* limited or unsatisfactory experimental data to deduce factors

Table 2. Dimensionless stiffness factors $M_b$ in function of pile and soil types

| Pile type / Soil type | Driven piles | Screw piles | Replacement piles |
|---|---|---|---|
| Sands | 30 up to 35 | 10 up to 25 | 2 up to 5 |
| Mixed | * | 5 up to 10* | 2 up to 5* |
| Clays | 100 up to 120* | 40 up to 60 | 2 up to 5* |

* limited or unsatisfactory experimental data to deduce factors

### 4.2 Validation.

Suggested transfer functions could be easily integrated into numerical programs to estimate the vertical pile settlement. A 1-

D Finite Element Model (FEM) using transfer functions was developed in this research (Figure 5). As illustration, a simple example is given. It concerns a screw pile "C4" installed in Limelette (cf. (A. E. Holeyman, 2001) for more details). The deformation parameters of t-z and q-z curves ($M_s$ and $M_b$), deduced from the back-analysis of SLT on the pile "C4", are used in the validation exercise. A good agreement is obtained between simulations and SLT results (Figure 6). The method allows not only the estimation of the pile head settlement under a given load but also the calculations of normal forces along the pile length.

### 4.3 *Application according to EC7/Belgian guidelines*

Before attributing the deformations parameters $k_s$ and $E_b$ from proposed values in Tables 1 and 2, the calculation of the maximum resistances ($t_{max}$ and $q_{max}$) is essential. The Belgian guideline "Rapport 19: *Guidelines for the application of the Eurocode 7 in Belgium according to NBN EN 1997-1 ANB; part 1: geotechnical design in ultimate limit state (ULS) of axial loaded piles based on Cone penetration tests (CPT's)"* is used. The ultimate values of the pile shaft and the base resistances (noted in this article as $q_{b,10\%}$ and $t_{10\%}$) are first calculated in accordance with Rapport 19 ($t_{10\%}$=$\alpha_{s,i}$ $q_{s,i}$ and $q_{b,10\%}$.=$R_b$/$A_b$). The sum of both components gives the total bearing capacity of the pile and corresponds, by definition, to a mobilized pile resistance at a pile base settlement equal to 10% of the pile base diameter. The maximum resistances ($t_{max}$ and $q_{max}$) could then be calculated using the expression of hyperbolic transfer functions (Eq. 3 & 4) as the following:

$$t_{max} = t_{10\%}(1 + 10M_s) \tag{12}$$

$$q_{max} \approx q_{b;10\%} \left(1 + \frac{\beta}{M_b.\frac{d_b}{10}}\right) \approx q_{b;10\%} \left(1 + \frac{4.55}{M_b.}\right) \tag{13}$$

For illustration purpose, the calculation method is applied to the screw pile B2 installed and tested in Sint-Katelijne-Waver (cf. (Maertens & Huybrechts, 2003) for more details). The pile is installed in tertiary clay (Boom clay) with 11.73 m length and with a nominal diameter equal to 0.41m. The selected deformation parameters are $M_s$=3 $10^{-3}$ and $M_b$=60. Results of the numerical program using these deformation parameters are given and compared to experimental results in Figure 7a. A good estimation of the load-settlement curve of the pile head is obtained with the proposed procedure especially for loads corresponding to the SLS load-range.

It is, however, important to emphasize on the importance of the ULS parameters ($q_{max}$ and $t_{max}$) to get a good agreement in SLS-design. In fact, the normal forces in function of the pile length, obtained from the numerical results, are compared to the experimental results for given pile loads during the SLT (Figure 7b).

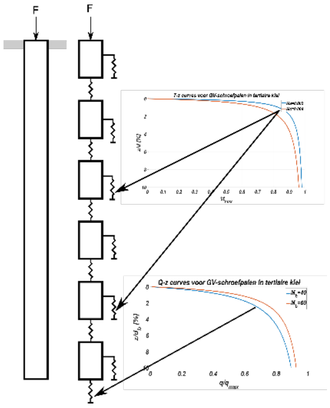

Figure 5. Structure of the developed numerical program for the estimation of the axial pile head settlement using transfer functions.

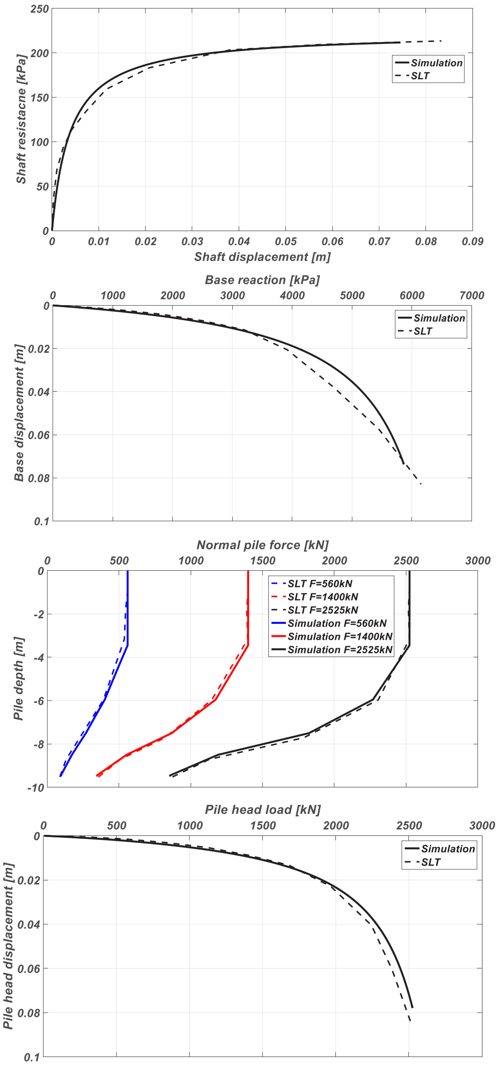

Figure 6. Comparison between simulations and SLT results for pile C4 tested in Limelette: a) unit shaft resistance b) pile base resistance c) normal load and d) pile head load-displacement curve

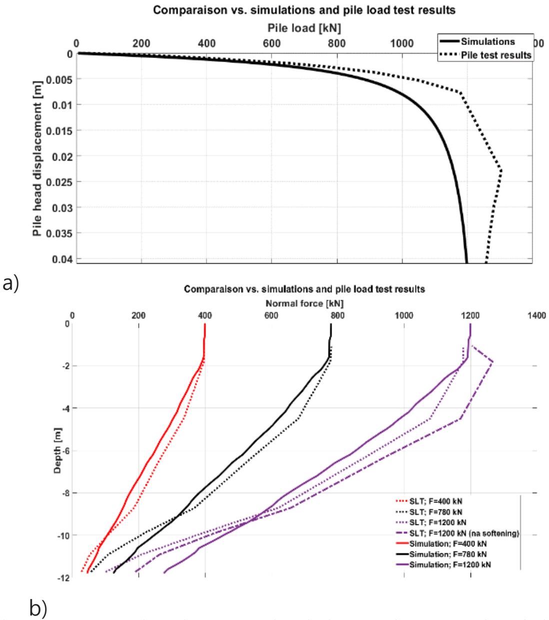

Figure 7: Comparison between. simulations and SLT results of pile B2 tested in Sint-Katelijne-Waver :a) pile head load-displacement curve and b) normal load distribution

The difference between the numerical and the experimental normal forces is explained by the divergence in the estimation of the ULS values ($q_{max}$ and $t_{max}$) calculated from the Belgian Guideline (Rapport 19) which could deviate from those obtained during the pile loading test (SLT).

## 5 PROPOSAL OF TYPICAL CURVES

Typical curves could be obtained from available experimental data where pile types and soil types are classified. The load displacement curves are normalized. This means that the loading is expressed as a percentage of the ultimate pile resistance and that the pile displacement is given as a percentage of the pile base diameter.

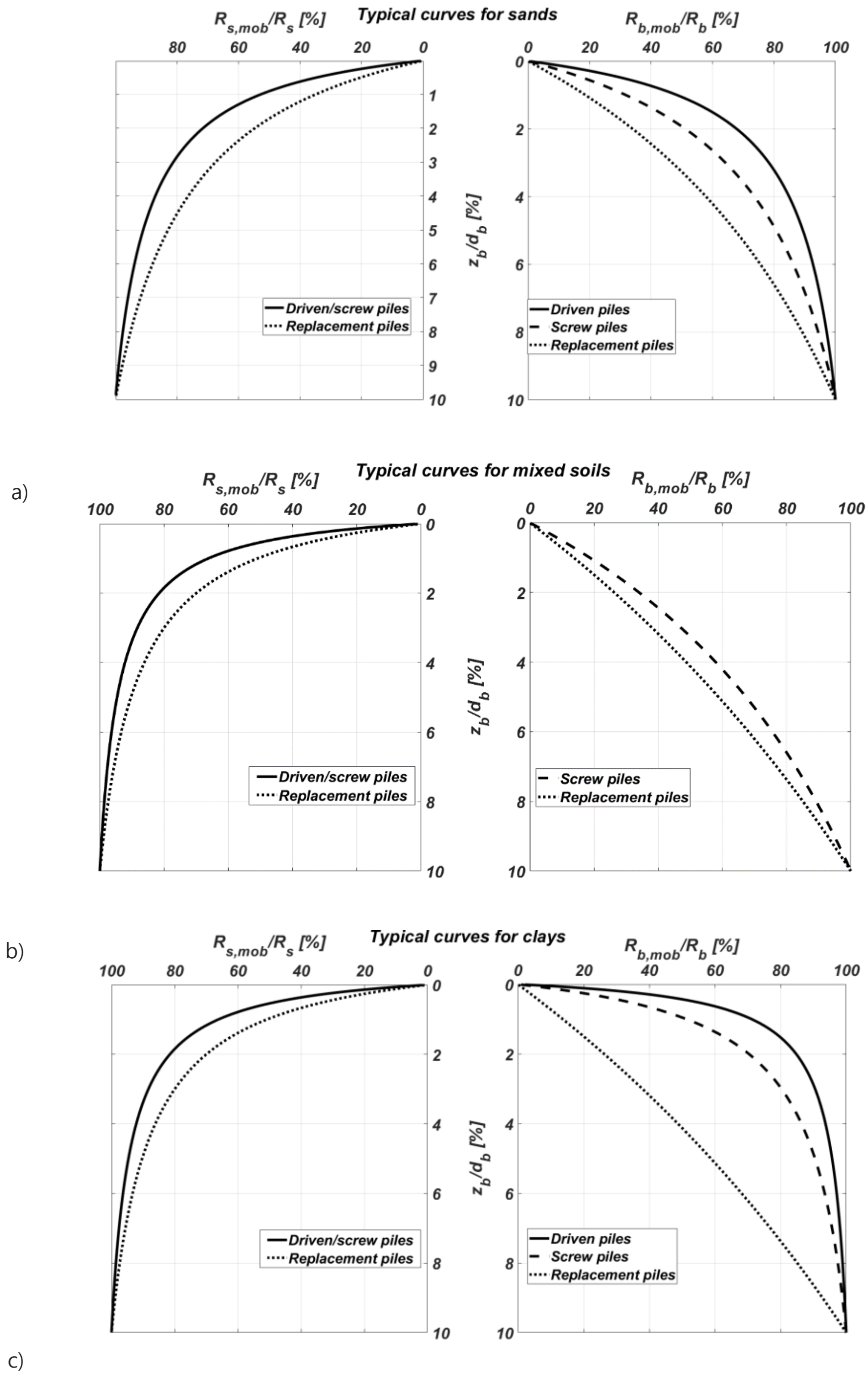

Figure 8: Proposal of typical curves in a) sands, b) mixed soils and c) clays

Since ultimate values of the pile resistance in Belgian practice are fixed at a pile base displacement equal to 10 % of the pile base diameter, all dimensionless curves intersect that same point. This analysis is performed for a large number of piles available in our database. The method is analogous to the principles of the Dutch standard (NEN 9997-1) and allows a rapid estimation of the pile displacement under vertical axial loads. ULS values from the Belgian guidelines (Rapport 19) and from the Belgian standard NBN EN-1997 +ANB are used.

Based on the analysis of the database, Figure 8 illustrates the proposed typical curves for driven, screw and replacement piles (continuous flight auger piles 'CFA' and bored piles) in respectively sands, mixed and clayey soils. The typical curves in Figure 8 offers rather a careful estimation of settlement based on experimental data.

The pile base displacement $z_b$ can be deducted based on typical curves. One can proceed as follows:

- Representative force ($F_{rep}$) in SLS design should first be determined.
- Pile base resistance $R_b$ and pile shaft resistance $R_s$ are then calculated based on Belgian Guidelines Rapport 19.
- Using Figure 8, for a given pile base displacement, one can estimate the percentage of the mobilized resistance at the pile base ($R_{b,mob}/R_b$) and at the pile shaft ($R_{s,mob}/R_s$).
- The predicted pile base displacement corresponds to the values where the sum of the mobilized pile base resistance ($R_{b,mob}$) and pile shaft resistance ($R_{s,mob}$), obtained from Figure 8, are equal to the representative force $F_{rep}$.

The pile head displacement could then be calculated by adding the displacement due to the elastic pile compression to the pile base displacement.

Since there is an analogy between typical curves and transfer functions, there is a possibility, in function of the ground layers for a given pile type, to combine typical curves for the pile shaft for a given soil type with typical curves for the pile base of an another soil type.

Nevertheless, the use of this simplified method with typical curves is most suitable in the case of rather homogeneous ground layers at the pile shaft. Besides, the method is not suitable for long piles since pile base reaction should be sufficiently mobilized.

## 6 CONCLUSIONS

Two methods are proposed in this paper for the estimation of the displacement for vertically loaded piles.

In the first method, hyperbolic transfer functions were developed based on the Winkler approach. These functions are integrated into a numerical program for validation (1-D FEM). The method gives not only a good estimate of the pile displacement but also the determination of the normal force distribution along the pile length.

The second method, with the so-called ‘typical curves’ is rather a pragmatic method, which allows a very fast estimation of the pile displacement. The method is only valid for homogeneous ground layers along the pile shaft (at least in the resistant layers) and for pile foundations with limited length (a minimal pile base mobilisation is needed).

Based on a large database, both methods were proposed for commonly used pile types and soil types in Belgium, with as a goal a better estimate of settlement for axially loaded individual piles in compression.

In the near future, the proposed methods will be transmitted to and discussed by the Belgian normalisation commission for Eurocode 7 with as an objective to convert it, in time, to a Belgian SLS method.

## 7 ACKNOWLEDGEMENTS

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