Foundation Settlement Calculations with the Pressuremeter Method Compared to Other Methods and Resulting Correlations

Calcul du tassement des fondations à partir de la méthode pressiométrique en comparaison avec d'autres méthodes, corrélations résultantes

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ABSTRACT: The purpose of this contribution is, on the one hand, to propose practical correlations between soil moduli by comparing the existing calculation methods for shallow foundation settlement, considering single footings with limited dimensions and large rafts. Particularly, the calculation method after Ménard on the basis of the pressuremeter modulus is compared with other more common methods on an international level based on other in situ tests and on laboratory tests. On the other hand, pile settlement calculation methods are presented, particularly using load-transfer curves, showing the advantages of the pressuremeter test in this matter and summing up some existing alternatives to the method after Frank & Zhao which is still prevailing in France today. The comparisons are made on a theoretical and mechanical point of view, followed by a calculation example in each case.

RÉSUMÉ : L'objectif de cette contribution est d'une part de proposer des corrélations entre les modules de sol en comparant les méthodes de calcul existantes pour le tassement des fondations superficielles, en considérant les semelles isolées de dimensions limitées et les radiers de grandes dimensions. En particulier, la méthode de calcul selon Ménard basée sur l'essai pressiométrique est comparée avec d'autres méthodes courantes d'usage international utilisant d'autres essais in situ ou en laboratoire. D'autre part, des méthodes de calcul du tassement de pieux sont présentées, en particulier à partir de courbes de mobilisation, montrant les avantages du pressiomètre sur cette question et résumant les alternatives existantes à la méthode de Frank & Zhao qui est encore largement prévalente en France aujourd'hui. Les comparaisons sont effectuées d'un point de vue théorique et mécanique, suivies par un exemple de calcul dans chaque cas.

KEYWORDS: pressuremeter test, cone penetration test, foundation settlement, shallow foundations, pile foundations
MOTS CLES : essai pressiométrique, essai de pénétration statique, tassement des fondations, fondations superficielles, fondations profondes

1 INTRODUCTION

Today, analytical or numerical methods are in general used to determine the settlement behaviour of complex foundation systems, like for example combined pile-raft foundations or soil reinforcement systems with rigid inclusions with load transfer platforms for example. For such sensitive systems, a settlement calculation and thus the use of relevant soil deformation parameters are essential. The reference cases of the corresponding simple shallow foundation and of the corresponding single pile have to be correctly represented in each project, and are considered to calibrate the deformation parameters, in general soil moduli, to be used in the next design steps. This contribution focuses on soil deformation parameters and settlement calculation methods for shallow foundations and piles, in accordance with the current tendency of a displacement-based design advocated by Eurocode 7.

Settlement calculations imply generally the choice of a soil modulus, corresponding to a given loading type, to given foundation dimensions and to a given load level (Ménard 1961, Combarieu 2006, Gambin et al. 2002). More than the calculation method chosen, the choice of the soil modulus is decisive for the final settlement value calculated.

In order to reflect the real behaviour of the soil in place as well as possible, in-situ tests are preferred for deriving soil parameters for the design. In this matter, the main advantage of the pressuremeter test (PMT), compared to the internationally widespread cone penetration test (CPT), is that it directly provides a soil modulus, defined for precisely known loading conditions. The main disadvantage of the PMT test is however that it is not commonly used and developed at the international scale, outside of France. Furthermore, the PMT-based design theory developed originally does not really apply for large rafts.

The first section presents correlations to determine an equivalent oedometer or an equivalent Young's soil modulus, required for numerical applications, from PMT or CPT tests, based on calibrations on the reference calculation case for footings and rafts. The second section deals with pile settlement calculation, still not very developed internationally because of the usually very small settlement of single piles, but becoming an increasing subject necessary for combined foundations and soil reinforcement systems, in particular since no loading test is in general available in the design phase. Due to very different stress paths in the soil between the shallow and deep foundation loading cases, the previous correlations for rafts and footings cannot be directly applied for piles, and detailed studies are still necessary in this respect in order to define deformation parameters for pile settlement without PMT test results.

2 SHALLOW FOUNDATION SETTLEMENT

2.1 *Calculation methods*

2.1.1 *Footings*

Settlement calculations methods of footings are in general linear with the applied load. This is in most cases sufficient, since the loading level remains in a serviceability range, verified by a separate bearing capacity check.

The PMT method for foundation bearing capacity and settlement design has been developed by Ménard, considering the analogy existing between the stress field in the soil under a footing and the cavity expansion stress field generated by the PMT test (Ménard 1963, Ménard and Rousseau 1962, Baguelin et al. 1978). Based on these mechanical similarities and on empirical observations, the formula for footing settlement (Eq. 1) has been developed, including a so-called structural coefficient α (Table 1).

Table 1. Structural coefficient α for PMT method translated from French application standard of Eurocode 7 NF P 94-261 (AFNOR 2013)

Soil type	Peat	Clay	Silt	Sand	Gravel
overconsolidated or very dense	-	1	2/3	1/2	1/3
normally consolidated or normally dense	1	2/3	1/2	1/3	1/4
overconsolidated weathered or loose	1	2/3	1/2	1/3	-

$$s=\frac{\alpha}{9\cdot E_{M,c}}\cdot(p-\gamma\cdot D)\cdot\lambda_c\cdot B+\frac{2}{9\cdot E_{M,d}}\cdot(p-\gamma\cdot D)\cdot B_0\cdot\left(\lambda_d\cdot\frac{B}{B_0}\right)^{\alpha} \quad (1)$$

B is the width of the footing and D its embedment, B_0 is equal to 0.6 m, γ is the unit weight of the soil above the footing base, $E_{M,c}$ and $E_{M,d}$ are weighted PMT moduli for heterogeneous soils, λ_c and λ_d are factors depending on the footing dimensions, and p is the loading stress (details in AFNOR 2013).

For specific highly-loaded cases, a proposal of non-linear correction of this expression considering the footing bearing capacity has been proposed by Combarieu (1988).

The oedometer method has been originally developed for rafts with large dimensions, where the ground is approximately unidimensionally loaded. However, an extension of this formula for footings with limited dimensions is widely used at international scale (“extended” oedometer method). Based on the stress profile under the footing calculated in linear elasticity, the settlement is determined using the initial void ratio e_0, the effective preconsolidation stress σ'_p, the effective initial and final stresses in a layer subdivision σ'_{v0} and σ'_{vf}, and C_s and C_c, the deformation parameters provided by the oedometer test (Eq. 2, i is the layer number). A modulus E_{oed} can be alternatively derived from the oedometer test for the studied load range, in that case a limit calculation depth corresponding to the depth where the additional stress reaches 20 % of the in-situ soil stress has to be considered. The use of reducing correction factors to take into account tridimensional effects is recommended, for example after DIN 4019, Skempton and Bjerrum or after Burland cited by Frank (1991).

$$s=\sum\frac{H_i}{1+e_{0,i}}\left[C_{s,i}\cdot\log\frac{\sigma'_{p,i}}{\sigma'_{v0,i}}+C_{c,i}\cdot\log\frac{\sigma'_{vf,i}}{\sigma'_{p,i}}\right] \quad (2)$$

In practice, oedometer tests are rarely carried out, and a oedometer modulus E_{oed} is derived by approximate correlations with the CPT cone resistance q_c after Sanglerat (cited in Eurocode 7 Part 2 2007), with partly very large factor spans depending on the soil type (Eq. 3 and Table 2).

$$E_{oed}=\beta\cdot q_c \quad (3)$$

Table 2. Values of β for CPT correlation (Eurocode 7 Part 2 2007)

Soil	q_c	β
Low-plasticity clay	$q_c \le 0.7$ MPa $0.7 < q_c < 2$ MPa $q_c \ge 2$ MPa	$3 < \beta < 8$ $2 < \beta < 5$ $1 < \beta < 2.5$
Low-plasticity silt	$q_c < 2$ MPa $q_c \ge 2$ MPa	$3 < \beta < 6$ $1 < \beta < 2$
Very plastic clay Very plastic silt	$q_c < 2$ MPa $q_c > 2$ MPa	$2 < \beta < 6$ $1 < \beta < 2$
Very organic silt	$q_c < 1.2$ MPa	$2 < \beta < 8$
Peat and very organic clay	$q_c < 0.7$ MPa $50 < w \le 100$ (%) $100 < w \le 200$ (%) $w > 200$ (%)	 $1.5 < \beta < 4$ $1 < \beta < 1.5$ $0.4 < \beta < 1.0$
Chalks	$2 < q_c \le 3$ MPa $q_c > 3$ MPa	$2 < \beta < 4$ $1.5 < \beta < 3$
Sands	$q_c < 5$ MPa $q_c > 10$ MPa	$\beta = 2$ $\beta = 1.5$

In any case, this extended oedometer method for footings does not take into account the increase of soil stiffness for small strains at depth, assumption on the safe side which derives from the initial application for large rafts, where no stress diffusion with depth is to be taken into account. This can lead to very conservative results.

Other less commonly used methods based on the standard penetration test, on the dilatometer or on the CPT test for sands (in particular after Schmertmann) exist as well and are described by Frank (1991).

2.1.2 *Large raft foundations*

Large raft foundations present no risk of ground failure, and linear settlement calculation methods are relevant.

The only well-proven and widely used method for this case, even if not deriving from in-situ tests, is the original oedometer method already described in 2.1.1., with the expression in terms of C_s and C_c from the oedometer test, or in terms of E_{oed} from the oedometer test for the relevant stress range, or with approximate correlations from CPT tests.

An “extended” PMT method has been proposed for large rafts (Baguelin 2005, AFNOR 2013), consisting in a calculation similar to the oedometer method cited in the previous paragraph, but with correlations for the moduli E_{oed} from the pressuremeter modulus E_M linked through the factor α from Table 1 (Eq. 4), even if the use of this factor for this purpose is very often debatable. This relationship is valid only for this ideal raft or slab application case with no stress diffusion under the foundation. This correlation method to determine an equivalent soil modulus (see section 2.3.2) should not be used if oedometer tests or CPT tests are available.

$$E_{oed}=\frac{E_M}{\alpha} \quad (4)$$

2.2 *Example*

2.2.1 *Configuration*

An existing site where CPT, PMT and oedometer tests from drill samples have been carried out closed to each other has been chosen, in spite of the particularly bad soil conditions corresponding to the limit of applicability of the PMT test (Figure 1). A simplified schematic representation of the soil configuration is presented in Figure 2. Case (a) corresponds to a rigid single footing, loaded with serviceability load level with no base failure risk, and case (b) represents the large raft foundation case with the same load.

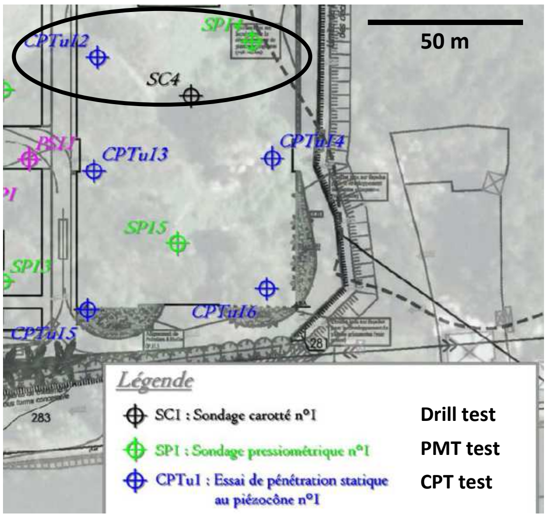


Figure 1. Example site with in-situ soil tests

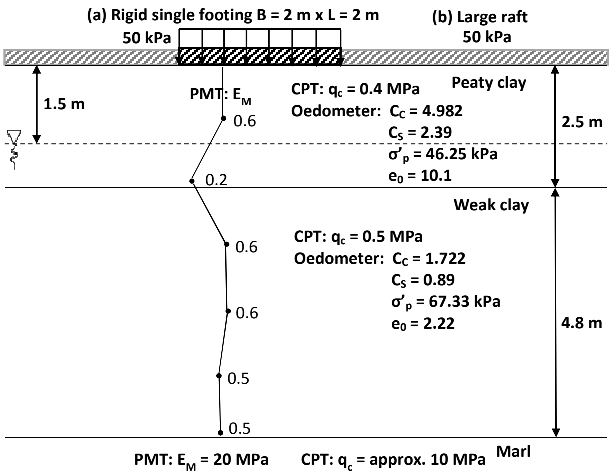


Figure 2. Example site: soil configuration and shallow foundation cases

2.2.2 *Settlement calculation*

The results of the settlement calculation for both cases (a) and (b) are presented in Table 3. In this example where all the major important tests are available, the pressuremeter calculation method is considered as the most reliable and reference method for the footing case (Eq. 1). The oedometer method based on the oedometer test is the reference method for the raft case (Eq. 2).

Table 3. Example site: comparison of settlement calculation methods and modulus calibration

Calculation method	Settlement (m)	
	(a) Footing	(b) Raft
PMT method	**0.084 Reference method**	0.882
Oedometer method with C_C/C_S	0.238	**1.042 Reference method**
Oedometer method with E_{oed} from CPT	0.017 to 0.33	0.868 to 17
Case-based correlation: calibration of E_{oed} with reference method	$E_{oed} = 2.2{\cdot}E_M$	$E_{oed} = 0.6{\cdot}q_c$

For the footing case, the reference PMT method gives a two to three times smaller settlement than the existing oedometer method, certainly because the last one does not correctly represent the actual stress-strain field with shear mechanisms under a footing. Depending on the exact organic content and water content of the soil layers, the CPT correlation method can only provide a very wide range for the factor β, between 0.4 and 8. If one considers the PMT method as the reference method, the equivalent oedometer modulus for following analytical or numerical applications would be $2.2{\cdot}E_M$ considering a calculation of the unimproved reference case. If one would prefer to consider the extended oedometer method as the reference case, the soil moduli would be the moduli corresponding to the equivalent calculation with the swelling and the compression factors C_s and C_c.

For the raft case, the reference oedometer method and the extended PMT method give similar results. Again, the correlation from CPT tests provides only a very wide and partly non-realistic range of up to 17 m. For following applications, the oedometer moduli corresponding to the oedometer test should be considered. Here one can see that this would correspond to a factor β equal to 0.6 for this soil and foundation conditions.

2.3 *Correlations between soil moduli*

An ideal design would imply to execute the calibration process presented in the example in section 2.2 based on the reference method chosen. Existing calibrations for common soil types in given regions may be possibly used for very similar conditions. If the relevant tests are missing for a given project, correlation indicative values given in international or national standards or recommendations may be used.

An informative annex in the French application standard of the Eurocode 7 NF P 94-261 (AFNOR 2013) proposes correlation values between an equivalent Young's soil modulus and the pressuremeter modulus for a footing on an homogeneous soil, to be used considering that these values can vary a lot for higher load levels and for larger footing dimensions (Table 4).

Table 4. Recommended ratio Young's modulus to PMT modulus (translated from AFNOR 2013)

Soil type		E / E_M
Clay	normally consolidated	4.5
	overconsolidated	3
Silt	normally consolidated	4.5
	overconsolidated	3
Sand	loose	4.5
	dense	3
Gravel	loose	6
	dense	4.5

If no oedometer test or no CPT values are available for a raft project and that soil moduli are necessary for numerical applications, the correlation presented in Eq. 4 may be used according to the French national application standard of Eurocode 7 (AFNOR 2013).

For the simplified case of a numerical model with a linear elastic soil modelling, the pressuremeter modulus may be correlated with an equivalent Youngs's modulus for the corresponding load type, based on the direct comparison of the Ménard formula and of the theoretical settlement equation of a plate on an elastic medium after Boussinesq, made by Combarieu (2006) for different footing dimensions.

3 PILE FOUNDATION SETTLEMENT

3.1 *Calculation methods*

Considering the necessity of pile settlement calculation methods today mainly in the aim of applications for highly-loaded or complex combined foundations and complex systems, non-linear methods representing the whole load-settlement pile behaviour are necessary. Simplified linear methods are presented however in particular by Poulos and Davis (1968) and by Randolph and Wroth (1978).

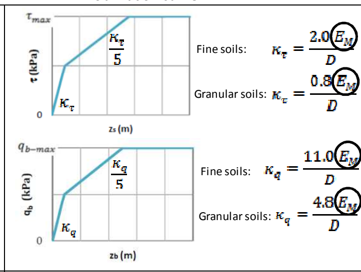
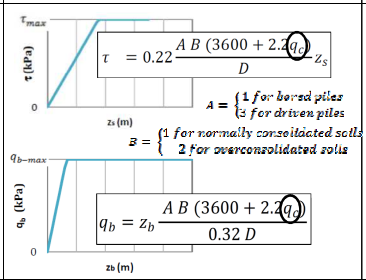
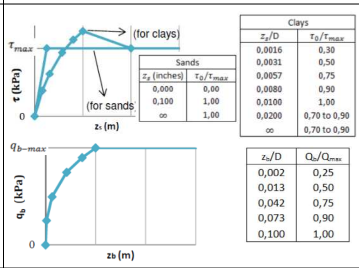
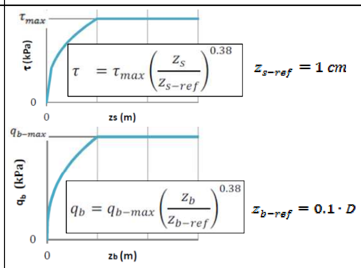
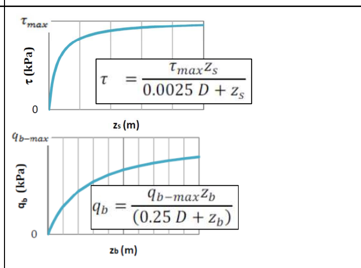
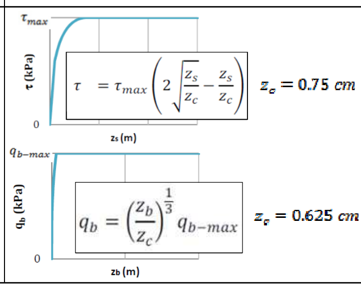
The main field of study about pile or rigid inclusion settlement concentrates today on so-called mobilization curves (load transfer or t-z curves) modelling the deformation behaviour of the whole pile and soil system. The mobilized resistance is related to the pile settlement in depth minus the free soil settlement (z_s for the skin friction curve and z_b for the tip resistance curve in Table 5). This method presents the advantage of controlling the maximum resistance values of skin friction and tip resistance by the design engineer, on the contrary to numerical methods, which require a check that the represented pile bearing capacity is realistic, due to the uncertainty in the determination of the soil resistance parameters needed (mainly shear parameters), which are rarely precisely documented. The response of a pile foundation modelled with load transfer curves, taking into account the pile compressibility as well, can easily be programmed numerically.

The mobilization curves calculation method has been first applied at large scale in France, in particular in the scope of the recent national project about rigid inclusions ASIRI (2012). Due to the common use of PMT in France and to the direct in-situ deformation parameter provided by this test, the very prevailing method used and well-proven by experience is the method after Frank and Zhao (1982) based on the pressuremeter modulus, initially developed for fine soils and then extended to granular soils (Frank 1985). A trilinear function is used (Table 5), which may be modified in a logarithmic function to simplify the mathematical resolution (Combarieu 1988).

A curve stiffness for small deformations (almost linear behaviour) can be defined as the initial slope of the curve. However, this stiffness cannot be directly related to correlations presented for shallow foundations in section 2, due to the very different stress fields. It can be namely noticed that a ratio of more than 2 exist between the fine and granular soil cases in the Frank and Zhao curve, which does not correspond to the ratio of equivalent moduli for shallow foundations proposed in Table 4 for example.

Even if they have in general not been proved by a regular use in the engineering practice yet, many construction methods of mobilization curves have been proposed by different authors, sometimes limited to given soil and pile types. Some of them are ready-to-use with complete input data from in-situ test parameters or limit settlements for full mobilization like in Table 5 (API 1993, Frank and Zhao 1982, Hirayama 1990, Krasinski 2012, Verbrugge 1981, Vijayvergiya 1977 cited in Pando 2003). Frank and Zhao (1982) and Verbrugge (1981) propose to control the initial curve slope only by a measured in-situ soil parameter, independently from the estimated maximum resistance. Other authors propose curve fitting parameters which have not been determined by the authors (Armaleh and Desai 1987, Fahey and Carter 1993 cited in Pando 2003, Kraft et al. 1981, Liu et al. 2004, McVay et al. 1989 cited in Pando 2003, Wang et al. 2012, Zhang et al. 2010).

Table 5. Some existing mobilization curves for pile skin friction (τ) and pile tip resistance (q_b)

	Mobilization curve	Soil type	Pile type
Frank & Zhao 1982	 Fine soils: $K_\tau = \frac{2.0 E_M}{D}$ Granular soils: $K_\tau = \frac{0.8 E_M}{D}$ Fine soils: $K_q = \frac{11.0 E_M}{D}$ Granular soils: $K_q = \frac{4.8 E_M}{D}$	Fine soils Granular soils	Bored piles Displacement piles
Verbrugge 1981	 $\tau = 0.22 \frac{A\,B\,(3600 + 2.2 q_c)}{D} z_s$ $A = \begin{cases} 1 \text{ for bored piles} \\ 2 \text{ for driven piles} \end{cases}$ $B = \begin{cases} 1 \text{ for normally consolidated soils} \\ 2 \text{ for overconsolidated soils} \end{cases}$ $q_b = z_b \frac{A\,B\,(3600 + 2.2 q_c)}{0.32\,D}$	Fine soils Granular soils	Bored piles Displacement piles
API 1993	 Clays: z_s/D ; τ_0/τ_{max}: 0,0016 ; 0,30 / 0,0031 ; 0,50 / 0,0057 ; 0,75 / 0,0080 ; 0,90 / 0,0100 ; 1,00 / 0,0200 ; 0,70 to 0,90 / ∞ ; 0,70 to 0,90 Sands: z_s (inches) ; τ_0/τ_{max}: 0,000 ; 0,00 / 0,100 ; 1,00 / ∞ ; 1,00 z_b/D ; Q_b/Q_{max}: 0,002 ; 0,25 / 0,013 ; 0,50 / 0,042 ; 0,75 / 0,073 ; 0,90 / 0,100 ; 1,00	Fine soils Granular soils	Bored piles Displacement piles
Krasinski 2012	 $\tau = \tau_{max}\left(\frac{z_s}{z_{s-ref}}\right)^{0.38}$ $z_{s-ref} = 1\ cm$ $q_b = q_{b-max}\left(\frac{z_b}{z_{b-ref}}\right)^{0.38}$ $z_{b-ref} = 0.1 \cdot D$	Granular soils	Displacement piles
Hirayama 1990	 $\tau = \frac{\tau_{max} z_s}{0.0025\,D + z_s}$ $q_b = \frac{q_{b-max} z_b}{(0.25\,D + z_b)}$	Fine soils Granular soils	Large diameter bored piles
Vijayvergiya 1977	 $\tau = \tau_{max}\left(2\sqrt{\frac{z_s}{z_c}} - \frac{z_s}{z_c}\right)$ $z_c = 0.75\ cm$ $q_b = \left(\frac{z_b}{z_c}\right)^{\frac{1}{3}} q_{b-max}$ $z_c = 0.625\ cm$	Granular soils	Displacement piles

In the German recommendation EA-Pfähle (DGGT, 2012), a direct method for a global pile load-settlement curve is proposed without the use of mobilization curves (Figure 3). The limit settlement for full skin friction mobilization s_{sg} is defined considering the total skin friction resistance. A displacement of 10 % of the pile head corresponds here to a full tip resistance mobilization.

$$s_{sg} \text{ (cm)} = \min (0.5 \cdot R_s \text{ (MN)} + 0.5;\ 3 \text{ cm})$$

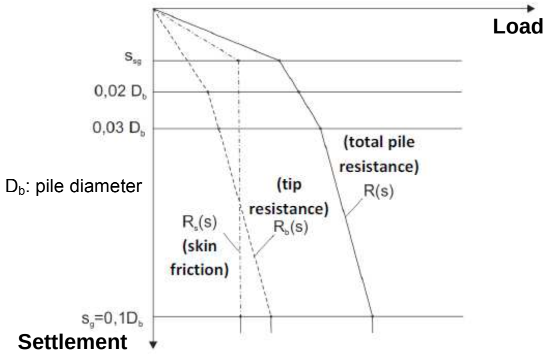


Figure 3. Pile load-settlement curve according to EA-Pfähle (DGGT 2012)

Without in-situ deformation parameters, that means without PMT test results, the only possible way to propose alternatives to the Frank and Zhao method would be an extensive statistical and empirical approach based on numerous instrumented pile load tests for different pile and soil types.

3.2 *Example*

3.2.1 *Configuration*

Figure 4 shows the example with the same soil configuration as in section 2. The maximum skin friction and tip resistance values are derived from the CPT results (AFNOR 2013).

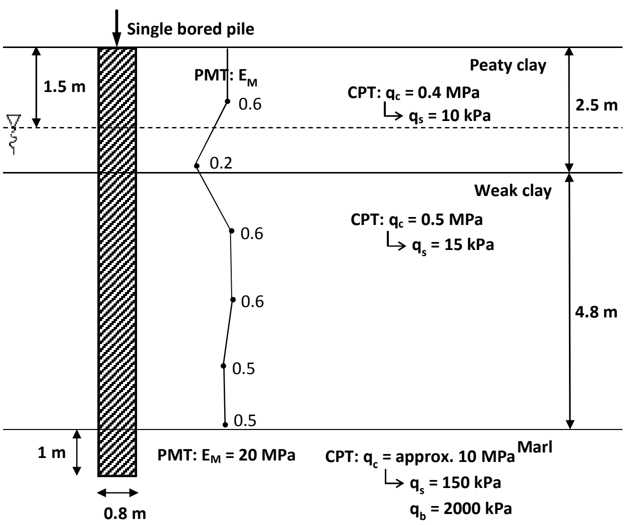


Figure 4. Example site: soil configuration and pile foundation

3.2.2 *Settlement calculation*

The results of the integration of the different ready-to-use mobilization curves available to get a global load-settlement curve for a displacement-controlled test are presented in Figure 5, together with the EA-Pfähle method. The same maximum resistance values q_s and q_b are imposed for all curves according to Figure 4, with a total bearing capacity of approx. 1630 kN. The fine soil and the bored pile present in this example do not always correspond to the cases defined originally by the different authors. Such a comparison may make it possible to extend those curves to other soil and pile types.

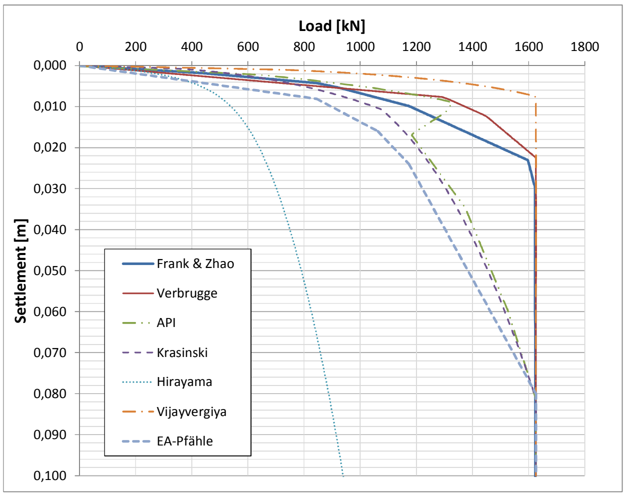


Figure 5. Example site: comparison of load settlement curves

The curve slope for relatively small displacements remains in a similar range for all presented authors. For higher load levels, higher differences between the authors are noticed, with in particular a very soft behaviour of the curve recommended by Hirayama (1990). The method after Frank & Zhao (1982) gives approx. an average behaviour of all other methods proposed on this example. The validity of the different methods should be checked by comparison with measurements from pile load test databases.

4 CONCLUSION

The PMT test presents advantages for predicting the foundation settlement, in particular the measured in-situ soil modulus and the good representation of the stress-strain field under footings and around piles. Nevertheless, it is interesting to find alternatives because of the limited use at present of this test at international level.

For shallow foundations, well-proven methods for settlement calculation exist. The direct pressuremeter method after Ménard is recommended for footings because of the overall consideration of the stress field and of the stress-dependent soil stiffness under the footing. The oedometer method based on oedometer deformation parameters is the only valid method for large rafts or slabs on a mechanical point of view. If no test with deformation parameters are available (only CPT for example), the correlation $E_{oed} = \beta \cdot q_c$ may be used, but only for well-known soils. If Young's moduli or oedometer moduli are necessary for following analytical or numerical applications, they should be determined case by case by calibration with one of the two above mentioned reference methods (for example for footings $E_{oed} = k.E_M$, k defined case by case). Informative annexes of standards may give indicative values for this correlation factor.

Pile foundation settlement is today still not sufficiently studied. The method with mobilization curves, used in particular in France with the efficient Frank and Zhao method based on the PMT modulus, seems to be a good way to understand and model the pile settlement behaviour in engineering practice. Alternatives to it, based either on other in-situ soil tests or on the definition of limit settlements for full mobilization, could be developed only empirically by an extensive comparison on numerous instrumented pile load tests.

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