Bearing capacity of displacement piles in layered soils with highly diverse strength parameters

Capacité portante des pieux de deplacements battus dans les sols stratifiés avec des paramètres fortement differés de la resistance

Gwizdala K., Krasinski A.
Gdansk University of Technology, Gdansk, Poland

ABSTRACT: Reliable prediction of pile bearing capacity including the installation effects is still a serious research and engineering problem. Computational analyses should be related to the load-settlement characteristics comprising entire range of loads, up to the limit state. European standard Eurocode 7 includes only the general rules and some calculation concepts. In the analytical method of pile bearing capacity calculation a commonly applied static formula, based on pile base and shaft unit resistances, is proposed. It is also recommended that the calculating procedures and the values of unit soil resistances used in the calculations would be verified by field tests done on real piles. In the paper the cases of bridge structures founded on driven displacement Vibro and Franki piles are presented. The design assumptions and computational results were verified by static load tests of piles (SPLT). Soil profiles and geotechnical parameters of soil layers have been determined by CPTU tests. One of static load tests was carried out on instrumented pile equipped with extensometers.

RÉSUMÉ : Prediction rèliable de la capacité portante des pieux avec les effets d'installation constitue toujours un problème important de l'ingénièrie et de la recherche. Analyse devrait inclure les caractéristiques charge-tassement dans le cadre entière de la charge jusqu'au l'état limit. Le standard Eurocode inclue seulement des règles et une concéption générales de calculs. Une méthode analytic de la capacité portante est proposée par la formule statique considerant unitaires resistances de base et du frottement latérale. Il est récomandé que la procedure de calcul ansi que les valeurs unitaires de la résistance au sol soit verifier par un essais de chargèment d'un pieu réel. Quelques cas des fondations de ponts posés sur les pieux battus Vibro et Franki sont présentés. Les assumptions de dimmensionement et les résultats de calcul sont vérifiés par le chargement statique des pieux (SPLT). Le profil du sol et les paramètres de couches du sol sont détèrminés par les essais CPTU. Un essais de chargement statique est réalisé avec un pieu instrumenté avec éxtènsomètres.

KEYWORDS: pile bearing capacity, settlement of piles, displacement piles

1 INTRODUCTION

Reliable prediction of bearing capacity and settlements of piles is still quite a difficult task either from theoretical as well as from practical point of view. The analysis of the transmission of loads by the construction into the subsoil in terms of full relation between load and settlement (*Q–s*) is more adequate. Currently in Europe and also in Poland general Eurocode 7 rules are applied.

According to the Eurocode recommendations, a design of pile foundations should be made using one of the following approaches:

a) based on the static load test results, the consistency of which with other comparable experiences has been proved by calculations or in some other way;
b) based on empirical or analytical calculation methods, the reliability of which has been confirmed by static load tests in comparable conditions;
c) based on dynamic load test results, the reliability of which has been revealed by static load tests in similar soil conditions and for the same type of piles;
d) based on the observation of the behavior of comparable pile foundations, provided that the data were verified by field tests (site investigations and soil testing).

It should be pointed out that basic method for the evaluation of *Q-s* curve are static load tests. An example of the relation of shaft, base resistances, total load and pile shortening are presented in Fig. 1. According to Eurocode principles, the conventional ultimate load Q_u, corresponding to the settlement equal to 10% of pile diameter ($s = 0{,}10D$) has been indicated. In such approach, partial coefficients for loads and partial coefficients for shaft and base resistances should be correlated with assumed ultimate load level determined from *Q-s* curve.

Characteristic bearing capacity of the pile determined on the basis of geotechnical parameters from ground test results can be calculated from the following formulae:

$$R_{c;k} = R_{b;k} + R_{s;k} \tag{1}$$

$$R_{b;k} = A_b \cdot q_{b;k} \tag{2}$$

$$R_{s;k} = \sum A_{s;i} \cdot q_{s;i;k} \tag{3}$$

where:

$q_{b;k}$ – characteristic value of the unit resistance under the pile base,
$q_{s;i;k}$ – characteristic value of the unit resistance over the pile shaft in subsequent soil layers,
A_b – calculated area of the pile base,
$A_{s;i}$ – calculated area of the pile shaft in the subsequent soil layers.

All over the world there exists quite a lot of methods for the calculation of pile bearing capacity. Also in Poland proposals of $q_{b;k}$ i $q_{s;i;k}$ calculation in relation to various technologies of piles have been elaborated, see e.g. Gwizdala 1997, Gwizdala 2011, Gwizdala and Steczniewski 2007, Gwizdala et al 2010, Krasinski 2012. When the pile bearing capacity is concerned, the range of settlement curve for the given method should be precisely defined (Fig. 1). Possibly, some reserve ΔQ may be included in relation to critical load Q_c (see Gwizdala 1997).

Comparison of bearing capacities calculated by various methods reveals significant differences. Exemplary results of calculations for Vibro pile and for data presented in Fig. 2 are collated in Table 1.

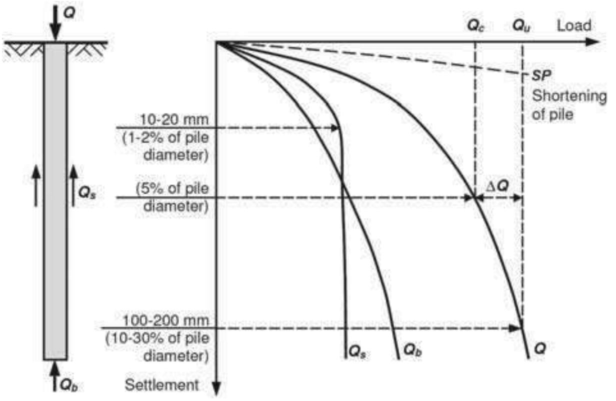

Figure 1. Generalized load-settlement curves of pile

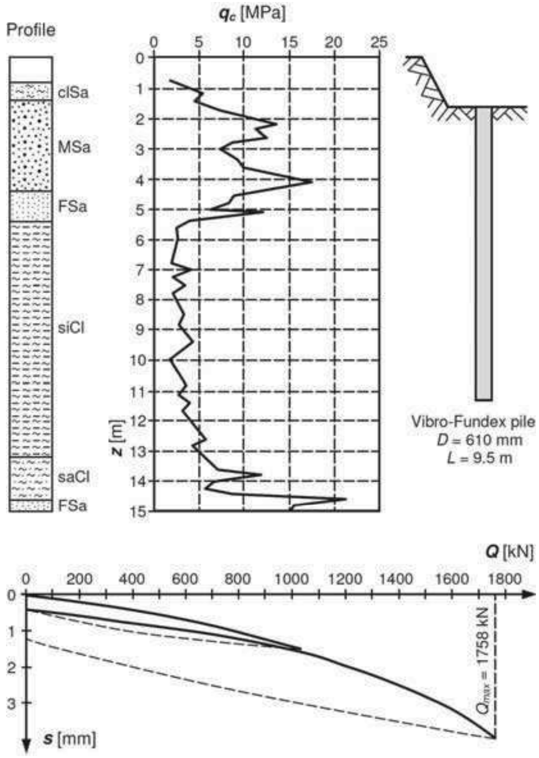

Figure 2. Data and static load test result of Vibro-Fundex pile, taken into calculation analysis

Currently big pressure is put on the development of calculation methods based on direct results of in situ tests, e.g. CPTU tests and making use of load-transfer *t-z* i *q-z* functions. Such method has been proposed by Gwizdala and Steczniewski 2007 (see example shown in Fig. 3) and for screw displacement piles by Krasinski 2012.

The problem becomes much complex for the piles installed in layered soils with highly diverse strength parameters. In such cases reliable results can be obtained from static load tests (SPLT).

Table 1. Static load test and calculation results for Vibro–Fundex pile

Method	Bearing capacity based on characteristic parameters [kN]	Correlation coefficients	Characteristic bearing capacity $R_{c;k}$ [kN]	Partial resistance factor γ_t	Calculated bearing capacity $R_{c;d}$ [kN]
Design load Q_r	–	–	–	–	1034.0
PN-83/B-02482 based on SPLT	1758.0 ($R_c = Q_{max,SPLT}$)	–	–	$k = 0.8$	1406.0
EN 1997-1; 2004 based on SPLT	1758.0 ($R_c = Q_{max,SPLT}$)	$\xi_1 = 1.4$ $\xi_2 = 1.4$	1256.0	1.1	1142.0
EN 1992-2; 2007 (DIN 1054)	2378.0	$\xi_3 = 1.4$ $\xi_4 = 1.4$	1699.0	1.1	1545.0
LCPC Bustamante & Gianeselli (1982)	1980.0	$\xi_3 = 1.4$ $\xi_4 = 1.4$	1414.0	1.1	1285.0
α – method API (1984)	1538.0	$\xi_3 = 1.4$ $\xi_4 = 1.4$	1098.0	1.1	998.0
Gwizdala & Steczniewski (2007)	2308.0	$\xi_3 = 1.4$ $\xi_4 = 1.4$	1648.0	1.1	1498.0

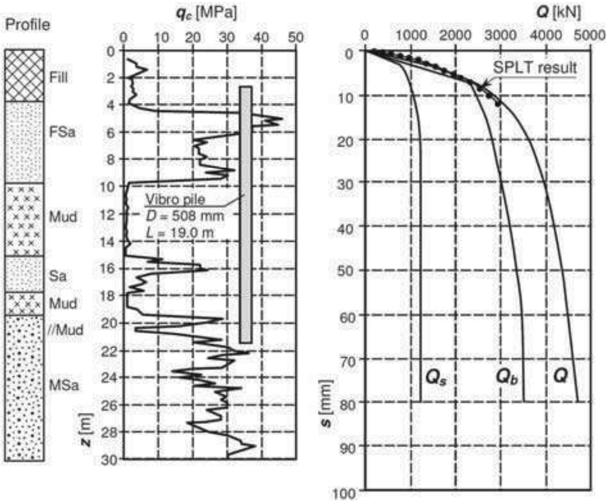

Figure 3. Example of Vibro pile calculation results obtained from load-transfer functions method (Gwizdala and Steczniewski 2007)

2. EXAMPLES OF IN SITU TESTS ON DRIVEN DISPLACEMENT PILES

Driven displacement piles are applied for constructions transmitting large loads and when small settlements are required, especially plastic settlements for designed load range. Very good characteristics of subsoil-pile interaction are obtained for driven cast-in-place displacement piles such as Virbo, Vibro-Fundex and Franki. (Fig. 3, 4 and 5).

2.1. *Tests on Vibro and Franki piles under bridge object of A1 highway*

In the frame of reconnaissance works for foundation of access flyover roads to large bridge over the Vistula river some tests on Vibro and Franki piles have been carried out. Vibro piles have the diameter of 508/560 mm and the length 25.4 m whereas Franki piles 560 mm and 23.5 m respectively. In Fig. 4 geotechnical conditions in the form of CPTU characteristics and settlement curves obtained from load tests are presented. Load –

settlement relations for both pile types are nearly linear. Due to conventional procedure of tests, the results did not provide any information regarding the distribution of loads transmitted by the shaft and by the base of piles into the subsoil.

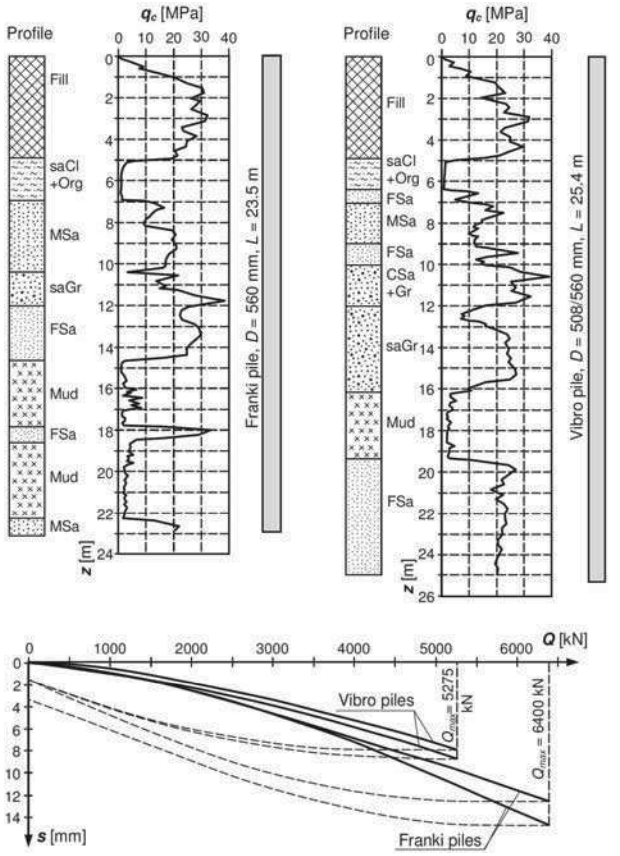

Figure. 4. Soil conditions and SPLT results of Vibro and Franki piles tested for bridge over the Vistula river project

2.2. *Tests on Vibro pile under road viaduct in Gdansk*

More advanced static load test has been carried out for ϕ508/560 mm Vibro pile installed under the foundation of road viaduct in Gdansk. In the test the distribution of load between shaft and base of the pile was measured. For this purpose a system of 7 extensometers have been installed inside the pile shaft in order to measure shaft strains. The principle of extensometric system work is commonly known, (Bustamante and Diox 1991, Hayes and Simmonds 2002, etc.). The assessment of axial load at various pile levels is based on the shortening measurement of individual pile sectors. Subsequently, the load transmitted into the particular soil layers over the pile shaft and under its base are determined.

Basic *Q-s* diagram representing settlement of the pile is presented in Fig. 5. In turn, the distribution of axial load in the pile for subsequent load levels obtained from the extensometric measurements is shown in Fig. 6. In Fig. 7 the results of further interpretation of the measurements in terms of unit friction resistances t_{si} over the pile shaft in particular soil layers and unit resistance under the pile base q_b are presented. The unit resistances have been expressed as a function of displacement of corresponding pile sectors.

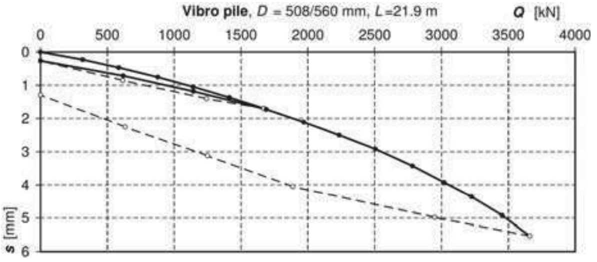

Figure. 5. Basic result from static load test of instrumented Vibro pile

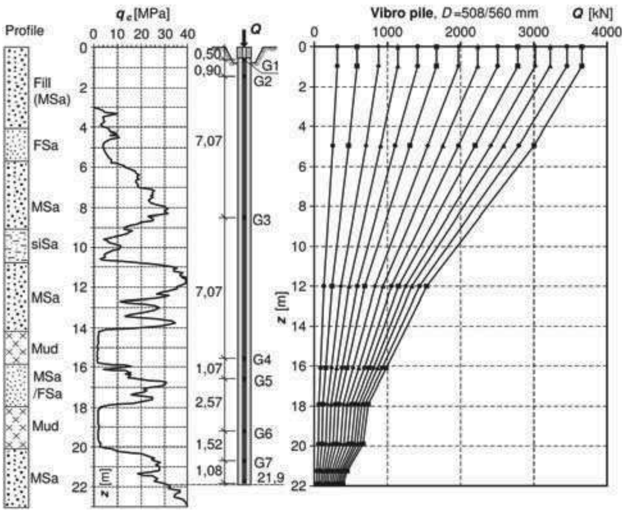

Figure. 6. Distribution of axial load in the instrumented Vibro pile

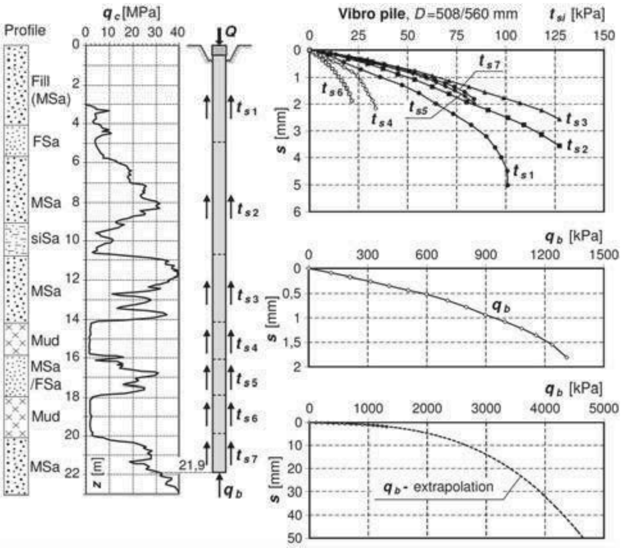

Figure. 7. Unit friction resistances t_{si} over the shaft in particular soil layers and unit resistance q_b under the base of instrumented Vibro pile

There are main observations and conclusions drawn from the analysis of the results of extensometric measurements:

- large part of external load applied to the pile head has been overtaken by the friction resistance of upper sandy soil layers which exist in the subsoil to the depth of 14 m, still over the mud layers;
- small portion of total load reached the level of pile base. The value of Q_b force transmitted by the pile base in the

final load phase was 400 kN approximately which is equivalent to 11% of total load Q_{max} = 3560 kN;

- essential portion of pile settlement (75% approximately) at the level of pile head (5.5 mm) is related to the shortening of the pile (4 mm approximately);
- settlement of the pile base in the final loading stage reached the value nearly 2 mm which explains small value of mobilized soil resistance under the base;
- values of mobilised unit friction resistances over the pile shaft t_s in sandy layers varied from 85 to 130 kPa whereas in mud layers from 25 to 35 kPa. Friction resistances in sandy layers directly under the soil surface (t_{s1}) reached full mobilization state corresponding to maximum value 100 kPa. In turn, the friction resistances of deeper sandy layers (t_{s2}, t_{s3}, t_{s5} i t_{s7}) did not reach maximum values due to small pile displacements against the soil occurring at the corresponding levels;
- mobilized unit resistance of the soil under the pile base q_b reached the value of 1300 kPa approximately and due to small displacements of the base is far from ultimate value. After extrapolation of the curve for the displacements corresponding to 10% of the pile diameter (50 mm), approximate value of limit unit resistance of soil under the base was about 4500 kPa.

Extensometric measurements performed during the load test revealed that upper subsoil layers took over large portion of the pile force which made difficult the reliable assessment of the bearing capacity of basic soil layers lying below. Thus the load applied in the load test should be much higher corresponding to Q_{max} of the order of 6000–7000 kN. However, due to capacity of loading stand it was not possible to apply such high loads. The described case may be a good example showing that the planning and interpretation of conventional loading tests requires always individual approach and analysis referred to the specifics of soil conditions, especially when we deal with layered subsoil. In such cases it is recommended to carry out the load tests accompanied by exetensometric measurements.

3 SUMMARY

Driven displacement piles of Vibro, Vibrex and Franki type have favorable load-settlement characteristics and reveal small settlements. General principles given by Eurocode 7 should aim at an unification of the methods for the calculation of bearing capacity of the pile. Current comparison of the calculation results obtained by various methods indicated significant differences in the assessment of the bearing capacity of the piles.

Experiences and comparative analyses with the results of load tests show that the most reliable results are obtained in terms of calculation methods which make use of in situ test results (CPT, CPTU, DLT, PMT). It would be of significant value to create the international database with complete static and dynamic test results of piles and the information regarding the measurements of soil resistances over the pile shaft and under the base referred to careful description of the subsoil and the in situ tests itself.

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