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Kazimierz GWIZDAŁA, Paweł WIĘCŁAWSKI

Gdansk University of Technology, Faculty of Civil and Environmental Engineering

Displacement piles – classification and new methods for the calculation of bearing capacity

Key words: displacement pile, bearing capacity, load–settlement, pile foundation, Eurocode 7

Introduction

When we are paying great attention to ecology in the broadest sense of the word, we should strive to use technology that will be environmentally friendly and have a minimal impact on the environment.

Deep foundation solutions are of particular importance, as they are in any case interference with the environment and the natural ground. The classic division of pile foundations includes:

- ready-made, prefabricated piles, prepared in advance, inserted into the ground using various techniques, e.g. wooden, reinforced concrete, steel and plastic piles;
- piles made in the ground, e.g. drilled, driven in with an extractor pipe, screwed in without a casing pipe (Gwizdała, 2010).

The classification of piles used so far is being modified due to the manufacturing technology. Today, displacement piles are increasingly used. As an additional element there are constantly appearing new materials used for pile construction. Another aspect is existence of the methods for calculating the load capacity and settlement of piles. Since 2010, after the introduction of the PN-EN:1997-1:2008 standard, it was necessary to change the approaches used so far based on years of experience and tradition. The old methods have been improved by defining coefficients allowing to extrapolate the settlement curve from the range of critical values to limit values.

To a large extent these are empirical procedures. The main determinant in the process of designing and then verifying the load capacity of piles has become the determination of the force that causes settlements equal to 10% of the pile diameter.

Classification of displacement piles

Displacement piles is a group of technologies whose main idea is to install or make piles without excavating the ground. In accordance with this definition, contained in PN-EN:1997-1:2008 standard, the displacement piles should be considered as hammered in, pressed in, vibrated and executed with the use of spreading drills (Fig. 1).

– easy adaptation of the current length to local soil conditions;
– possibility of ongoing control by measuring the momentum and verifying the depth into the ground;
– possibility of ongoing control using dynamic formulas and dynamic tests;
– possibility of making inclined piles in a large inclination range.

Wide use of prefabricated piles is possible thanks to a wide range of cross-sections, from 20 × 20 to 45 × 45 cm every 5 cm, respectively, and different lengths (Gwizdała, 2010).

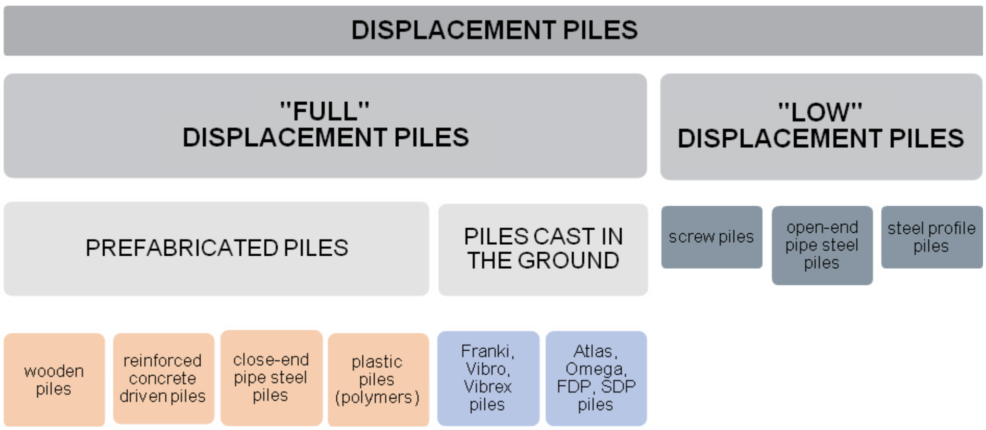


FIGURE 1. Classification of displacement piles

Prefabricated reinforced concrete driven piles

Prefabricated reinforced concrete driven piles are known and used in various types of construction in Poland for many years. Their use is determined by the following advantages:

– execution speed, from 200 to 350 m piles per day using piling machine;
– considerable pile length, using combined piles up to 50 m;

Pipe steel piles

Steel piles are most often used in hydrotechnical construction, marine and bridge construction. Made of closed or open steel pipes with diameters from 400 to 2,500 mm. Recently, they have very often been used to build offshore wind turbines foundation as monopiles

FIGURE 2. Types of piles: a – prefabricated reinforced concrete piles (photo by K. Gwizdała); b – pipe piles (photo by K. Gwizdała); c – steel profile piles (©Thyssen Krupp); d – wooden piles (photo by K. Gwizdała); e – plastic piles (©Akerpol.pl); f – disc screw pile (©sw.birmiss.com)

with diameters of up to several meters (Fig. 2).

Steel profile piles, combined elements

Sometimes there ate used steel piles from sheet piling walls and sections. Combined piles can transmit vertical forces, but above all significant bending moments. These solutions have been successfully used for many years on the Polish coast for hydrotechnical and marine construction.

Wooden piles

Wooden piles are the oldest type of displacement piles. Properly applied, they are an economic and safe way of founding objects, as evidenced by the numerous historic buildings founded on piles. The advantages of wooden piles include:

– low material cost;
– durability in optimal conditions over 100 years (under water);
– resistance to stray currents;
– do not require corrosion protection;
– are driven using typical pile driver equipment.

Plastic piles

In the face of growing environmental concerns, new products made of recycled plastic or vinyl are appearing on the market. Among these products are also piles and sheet piles. The advantage of the material is that it can be processed with standard tools for wood and metal.

The material from which they are made is characterised:

– waterproofing;
– resistance to rotting and corrosion;
– no reaction with water and soil;
– resistance to chemicals, salt and sea water.

Screw piles

The technology consists in screwing a pipe with a screw-shaped spiral into the ground. To make it, pipes with high resistance to torsional moments caused by significant forces needed to sink are required. Another solution in this subgroup are disc-shaped bolt piles, designed to carry low loads, consisting of perches and spiral carriers. The advantage of this design is the possibility of increasing the length of piles by adding more segments. The load-bearing capacity of the pile can be increased by injecting it through a rod. The piles reach a load capacity of up to 500 kN.

Vibro, Vibrex and Franki piles

Vibro, Vibro-Fundex, Vibrex piles are fully displacement piles made in the ground, without bringing the ground to the surface. The most commonly used shank diameters are 457 and 508 mm, the diameter of the lost steel base is larger and ranges from 500 to 700 mm. Enlarged diameter of the steel shoe causes that we get immediately a pile with an extended base (Fig. 3a). Pulling the pipe out with a vibrator compacts the concrete and ensures that the pile shaft is well connected to the ground. Vibro-Fundex piles are characterized by very favourable characteristics, i.e. high load capacity for small settlements. Franki piles are one of the oldest deep foundation techniques. After some modifications, this technology is still used today with great success. The diameter of a steel pipe usually ranges from 500 to 600 mm, length from 12 to 20 m. The steel pipe is driven into the interior with a dry concrete plug using a free fall tup insert. Knockout of the cork with a rammer causes the formation of an enlarged base (Fig. 3b), and successive lifting of the steel pipe using a winch with simultaneous concrete filling – forming a sideway well connected with the surrounding ground (Gwizdała, 2010).

a b

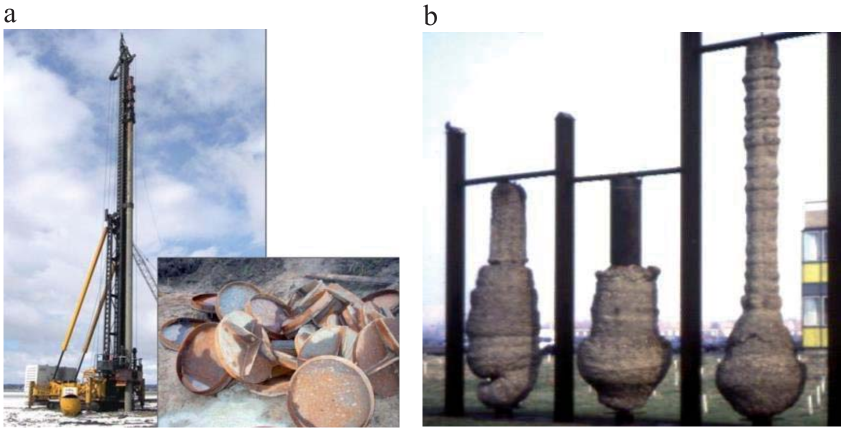


FIGURE 3. a – execution of the Vibro pile and steel base (photo by K. Gwizdała); b – Franki piles (photo by K. Gwizdała)

Atlas, Omega, FDP, SDP piles

A subgroup of displacement piles made by means of augers of special construction and geometry. The drill is immersed in the ground without a casing pipe and excavation of ground material to the surface (Fig. 4). Moving the soil horizontally to the sides and vertically and diagonally at the base causes the soil to compact in the immediate vicinity of the pile, increase in the horizontal pressure component and generate pore water pressure in the soil. Pile diameters usually range from 400 to 600 mm and length up to 30 m. The piles are characterized by high load capacity and small settlements, however, they require drilling machines with a sufficiently high torque (Gwizdała, 2010).

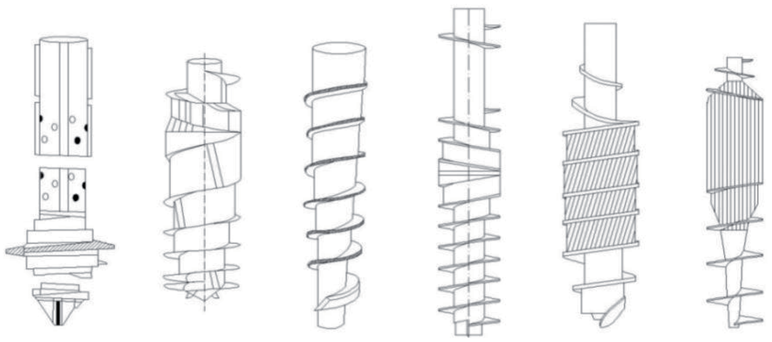


FIGURE 4. Drills of screw displacement piles (Gwizdała, 2013)

Capacity of displacement piles

According to the PN-EN 1997-1:2008 standard, we distinguish four methods of designing pile foundations based on:
- the static load test results (SPLT);
- empirical or analytical calculation methods;
- the results of a dynamic test (DLT);
- observations of the behaviour of comparable pile foundations.

Interpretation methods for static load tests

The only reliable source of verification is the static test load carried out for subsidence and limit-bearing capacities, or to the extent that it allows for their precise determination. In the literature you can find proposals for methods of extrapolation of incomplete *Q–s* curves, which enable the estimation of settlement limits and pile-bearing capacity (Gwizdała, 2013). They do not take into account such factors as: the way the piles are made; the roughness and stiffness of the pile shaft, but only the general trend of the *Q–s* curve. The most popular methods of curve extrapolation from a static survey include: PN-83/B-02482 standard, Gwizdała, Brinch-Hansen, Chin, Davisson (Gwizdała, 2013;

Więcławski, 2018), Meyer–Kowalow (Meyer & Szmechel, 2012) method and many more.

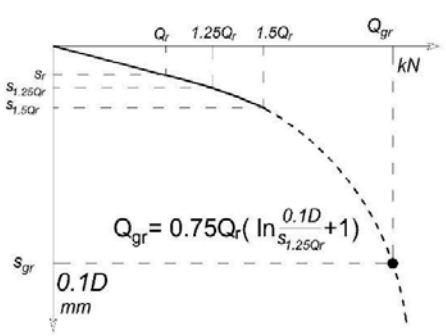
In tests carried out on prefabricated reinforced concrete, pipe, wood and plastic piles, which have a smooth surface and a regular base surface, "full" settlement curves are obtained. In this case, the conventional ultimate limit resistance can be read directly from the graph or extrapolated to this value without fear of major error. As a verification, a pile drive analysis (PDA) can also be used. This is not the case with piles formed in the ground by means of vibrators, which compacts the ground around the sidewalk and with an extended base, as is the case with Vibro, Vibrex and Franki technology.

The scattering of the minimum to maximum load limit value obtained by means of different methods of interpreting static loads for Vibro piles is almost 50%. Recently, Więcławski (2018) proposed an empirical method based on more than a hundred real curves from test loads for this technology. The condition for the application of the method is the quasi-linear character of the settlement curve resulting from the location of the pile base in non-cohesive soils, mainly compacted medium and fine sands.

In standard test loads, the result is a settlement curve and this is sufficient to verify the load capacity of the pile. However, a common procedure is to determine the load distributions for each part of the pile. Various extensometer or fiber optic systems are used for this purpose for all pile technologies. Research of this nature for displacement piles, both precast reinforced concrete and ground-based, driven and screwed, was popularized by Krasiński (Krasiński, 2012; Gwizdała, 2013; Gwizdała & Krasiński, 2013).

In his research Krasiński used a neostrain system, in the form of a chain of string extensometers mounted in canals inside the pile. The results of the test beyond the total settlement curve are the friction curves at the side of the pile depending on the depth and the resistance curve at the base of the pile. Friction on the sidewalk is taken into account in the test, depending on the ground layer.

a



b

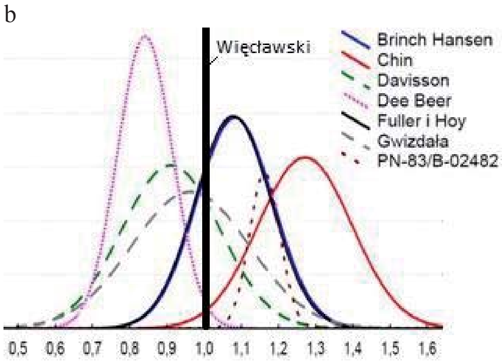


FIGURE 5. a – the Więcławski method of limiting load capacity based on extrapolation of the settlement curve for Vibro piles; b – distributions of the limit load value obtained with different methods in relation to the values from the Więcławski method (Więcławski, 2018)

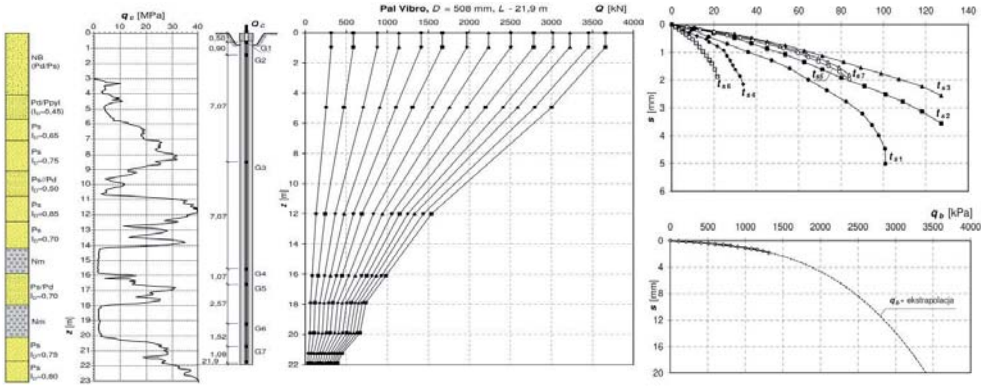


FIGURE 6. Interpretation of the static test load with resistance distribution along the side surface and under the pile base using the neostrain system (Gwizdała et al., 2013)

Analytical methods for determining the value of bearing capacity

Assessing the load capacity and settlement of a single pile in complex geotechnical conditions is a very difficult engineering task. They're determined on a basis:

– calculations made on the basis of soil tests;
– correlations, empirical or semi-empirical methods based on field tests and static load test results;
– methods based on transformation functions, determined analytically or in model tests;
– finite element methods (FEM), boundary element methods (MEB) or other matrix solutions.

More and more rarely, methods of determining the geotechnical parameters of the subsoil on the basis of statistical methods and the so called B method popular in Poland are used. For design, we use the soil parameters from in-situ tests with high efficiency, among which the CPT results are the most important. On the basis of the probe measurements, we can apply direct methods and estimate the load capacity of the piles. The standard PN-EN 1997-1:2008 does not impose a calculation method, it proposes to use for example the methods from the old German standards DIN 1054, the Schmertmann method, the Dutch method of DeRuiter and Beringen (Gwizdała, 2010; Gwizdała, Brzozowski & Więcławski, 2010). The only condition is the application of an appropriate calculation approach, which involves the selection of appropriate correlation and safety factors.

The French method of Bustamante and Giasenelli – LCPC and the Gwizdała and Stęczniewski method have been used in Poland for years. The popularity of the latter results from the definition of individual relationships for local conditions and the detailed classification of the layout of the subsoil layers, hence a specific scheme is used for the calculations. An additional advantage is that we take into account the technology of making piles, for Vibro we have individual load capacity coefficients (Gwizdała & Stęczniewski, 2004; Gwizdała, 2010).

$$q_{bu} = \psi_1 \cdot \overline{q}_c \, , \; q_{sui} = \frac{\overline{q}_{csi}}{\psi_{2i}} \qquad (1)$$

where:

q_{bu} – unitary limiting resistance under the base of the pile,

$\overline{q}_c$ – average resistance under the probe cone at the base of the pile,

q_{sui} – unitary limiting resistance at the pile side within the i-th calculation layer,

$\overline{q}_{csi}$ – averaged resistance under the probe cone within the layer.

P_A = 1.0 MPa.

The prediction of the full load–settlement characteristics is reliable. Such a solution is provided by methods based on a hyperbolic model of the settlement curve, adopted mainly in transformation functions, and a complex, linear-exposure model, which reflects with great accuracy the interaction of the ground with displacement piles. The transformation functions have great practical applications. They allow for non-linear load–sitting relationships. Functions are used to describe the relationship between the resistance at the side of the pile and displacement (t–z curve) and the relationship between the resistance under the base of the pile and its displacement (q–z curve). In the literature there are many items containing the description of transformation functions, among others Gwizdała, Vijayvergiya, Van Impe, Randalph and Wroth or Hirayama (Gwizdała, 2010). Analytical methods are most often combined with transformational functions. On the basis of the classical approaches, the values of the side and base resistance are determined, and using the appropriate function t–z and q–z, the possible course of the settlement curve is determined for the calculated limit resistance and accepted limit settlements (Gwizdała & Krasiński, 2016).

$$q_b = q_{b;f} \left(\frac{s_b}{z_f} \right)^{\beta} \quad \text{for } q_b \le q_{b;f}$$

$$q_s = q_{s;\max} \left(\frac{s_s}{z_v} \right)^{\alpha} \quad \text{for } q_s \le q_{s;\max} \qquad (2)$$

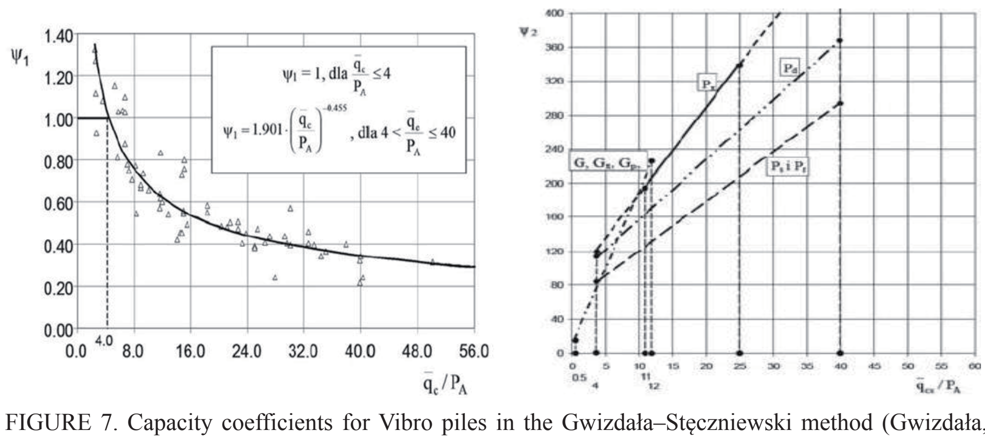


FIGURE 7. Capacity coefficients for Vibro piles in the Gwizdała–Stęczniewski method (Gwizdała, 2013)

where:
α, β – function exponent,
z_v – pile sidewall displacement at which maximum soil friction is mobilized $q_{s;\max}$,
z_f – displacement of the pile base at which boundary soil resistance is mobilized $q_{b;f}$ under the base.

TABLE 1. Proposed parameters of transformation functions

Specification	z_v	α	z_f	β
Driver precast concrete piles	0.01D	0.50	0.05D	0.25
Vibro piles	0.01D	0.25	0.05D	0.25
SDP, SDC, CMC	10 mm	0.38	0.1D	0.38

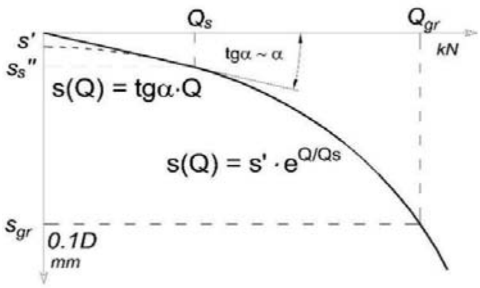


FIGURE 8. Idea of the Więcławski method and correlations to determine the settlement curve for Vibro piles in medium sands (Więcławski, 2016)

The philosophy of direct determination of the settlement curve based on CPT test results is particularly useful for the purpose of optimal design and use of the load-bearing capacity of piles.

This is opposed to the proposal of the Więcławski empirical direct method for Vibro piles. The main assumption of the method is a two-phase load–setting characteristic. This means that there is initially a linear displacement which includes the mobilisation of resistance at the side of the pile and then a non-linear displacement as a result of exceeding the boundary friction and mobilisation of resistance under the base of the pile.

$$\frac{s''}{Q_s} = 2D\left\{0.022\left[\frac{q_{c,avg}\cdot L}{2L_{gn}}\right]^{-D}\right\} \tag{3}$$

$$s' = 1.17\ln\left(\frac{s''}{Q_s}\right) + 8.91\,(\text{for MSa})$$

where:
Q_s – load initiating the elasto-plastic phase of the pile–soil interaction for settlement s_s'',
D – piles diameter,
$q_{c,avg}$ – average resistance q_c from *CPT*,
L – piles length,
L_{gn} – depth of the pile base in medium sand,
s' – initial point of non-linear load––settlement function for Q = 0 kN.

The above dependencies (3) are of universal character for Vibro piles made in soils stratified with a base in medium sands throughout Poland (Więcławski, 2016). Detailed guidelines and relationships for other conditions are presented in the author's work. An important aspect is that the method can be adapted to specific local conditions. An example is the adaptation of the method to the geotechnical conditions prevailing in coastal areas in sea ports in Gdynia and Szczecin (Więcławski, 2019).

The method is characterized by high accuracy comparable to the methods of interpretation of static and dynamic test loads.

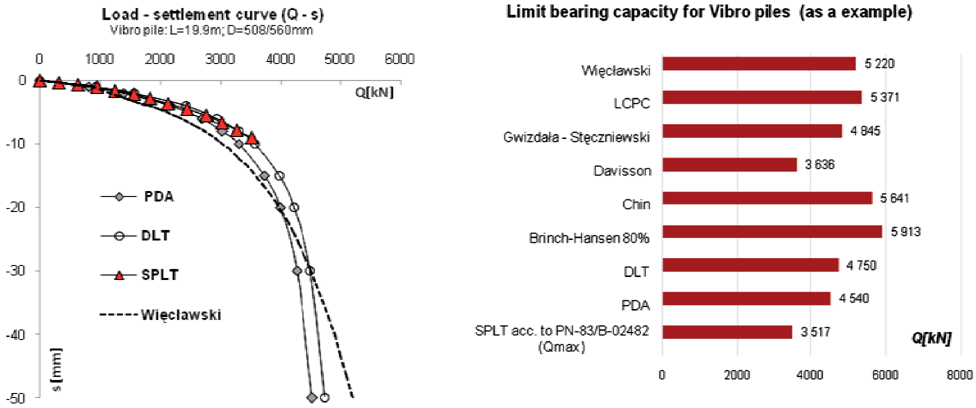


FIGURE 9. Summary of the results of the limit load capacity obtained on the basis of analytical methods and field tests for Vibro pile: L = 19.9 m, D = 508/560 mm (Gwizdała, 2013)

Conclusions

The displacement piles allow for rational and economic execution of deep foundation in any soil conditions (Biliszczuk, 2019). It's affecting it:

– greater control of the piling process than in the case of drilled piles;
– immediately after piling, the next works can be started, without waiting for the concrete to set, which generally speeds up the foundation works;
– the displacement piles technology does not require excavation, storage or removal of soil from the excavated material, which is cumbersome in the case of drilled piles and weak-bearing soil (especially in built-up areas).

Recent calculation methods make it possible to precisely assess the interaction between piles and the ground centre. The trend of forecasting the full characteristics of the Q–s pile affects the development of design methods, the main criterion of which is settling. This approach allows the full potential of the pile structure to be exploited for load-bearing purposes. Displacement piles are able to carry significant vertical and horizontal loads, which are influenced by changes in the state of stress in the ground, resulting from their technology.

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Summary

Displacement piles – classification and new methods for the calculation of bearing capacity. The paper presents technological changes concerning not only the method of construction, but also the materials used. Another aspect is the methods of calculating the load-bearing capacity and settlement of piles. With acceptance for use the PN-EN:1997-1:2008 standard in 2010, it was necessary to change the approaches applied that based on many years of experience and tradition. The best method in this case is to forecast the full load-settlement characteristics. On the basis of the collected data, a comparative analysis of particular displacement piles technologies was made. The usefulness of individual methods of load-bearing capacity calculation depending on the pile technology was determined.

Authors' address:
Paweł Więcławski
(https://orcid.org/0000-0002-8681-7083)
Politechnika Gdańska
Wydział Inżynierii Lądowej i Środowiska
ul. Narutowicza 11/12, 80-233 Gdańsk
Poland
e-mail: pawwiecl@pg.edu.pl