Studia Geotechnica et Mechanica, 2023; 45(s1); 282–292

Special Issue 19th KKMGiIG

Open Access

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Estimation of Screw Displacement Pile-Bearing Capacity Based on Drilling Resistances

https://doi.org/10.2478/sgem-2023-0014
received January 15, 2023; accepted June 23, 2023.

Abstract: This article presents an engineering, empirical method of estimating the bearing capacity and settlement characteristics *Q-s* of screw displacement piles and columns, based on soil resistance encountered during the drilling to form piles/columns in the ground. The method was developed on the basis of correlation analyses of the test results of 24 piles made during the "DPDT-Auger" research project (Krasiński et al., 2022a). In the proposed method, the load capacity of a screw displacement pile is estimated using two main parameters of auger screwing resistance: torque M_T and the number of auger rotations per depth unit n_R. The method applies to piles and columns made with a standard *screw displacement pile* (SDP) auger and with the proprietary, prototype DPDT (*displacement pile drilling tool*) aguer, patented in Poland (2020). Based on the estimated ultimate capacities of the pile shaft and base, an approximate method of predicting the pile settlement characteristics *Q-s* was also proposed, using the transfer function method. This article describes a correlation procedure of field test results together with their statistical analysis and presents a method of estimating the pile-bearing capacity based on correlation results. A calculation example is also provided. The conclusion looks at the useful practical applications that could be found for the proposed method.

Keywords: screw displacement pile; pile load capacity; pile auger; soil resistance during pile formation.

1 Introduction

In the case of driven piles, there are methods of estimating load capacity based on driving resistance using the so-called dynamic formulas (Holeyman & Skov, 1999). Similarly, in the case of screw displacement piles, it seems to be possible to estimate load-bearing capacity on the basis of resistance measured during the drilling of a pile hole in the ground with a displacement auger. In the author's opinion, possible formulas and methods in this matter can mainly be of an empirical nature, as in the case of, for example, estimating the pile-bearing capacity based on *cone penetration test* (CPT) results. The need to develop such a method stems mainly from practice as reported by pile contractors.

The issue of soil resistance while drilling a pile hole with a displacement auger is one of the most complex problems in pile construction technology. These resistances reach high values in noncohesive soils, making it difficult to obtain deeper pile penetration in load-bearing soil layers. This necessitates the use of high-powered drilling rigs to provide the torque. In cohesive soils, however, resistances are lower, but the process of soil expansion by the auger generates a large excess of water pressure and soil structure degradation (mainly of cohesion), which may result in the deterioration of pile–soil interaction, and thus pile-bearing capacity. An additional problem is that high screwing resistances (especially high torque) in noncohesive soils do not always translate into high load-bearing capacity and pile stiffness. The author has encountered such situations several times in practice (Krasiński, 2013). A similar problem is unlikely to occur in driven piles, where usually high driving resistances coincide with high pile capacities and stiffness.

Not much has been published so far in the literature on the relationship between the resistance of pile formation by a displacement auger and the pile-load capacity. NeSmith (2003), who was one of the first to deal with this issue, expressed the displacement pile-driving resistance as the installation effort (*IE*) parameter. He proposed to calculate the *IE* on the basis of drilling parameters, such as the torque and penetration rate of the auger:

$$IE = PRI \cdot TI \ [\text{-}] \tag{1}$$

in which: *PRI* – penetration rate index, *TI* – torque index.

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The values of *PRI* and *TI* are calculated as:

$$PRI = 1/(PR/PR_{base})^{0,5} \text{ [-]} \quad (2)$$

$$TI = 2{,}78/(t_{fp}/T_{base})^{1.36} \text{ [-]} \quad (3)$$

where: *PR* – penetration rate [m/min], PR_{base} – base (reference) penetration rate equal to 6,1 m/min, t_{fp} – oil pressure in the rotary motor [bars], T_{base} – base (reference) torque level equal to 100 bars.

Using the test results of several piles from various construction sites and projects, NeSmith analyzed correlations between the screwing resistance and the load capacity of piles. He obtained an approximately linear correlation between the summed value of drilling effort (*SumIE*) and the ultimate bearing capacity of pile shaft (Fig. 1a), and a semilogarithmic correlation between *SumIE* and the ultimate total bearing capacity of the pile (Fig. 1b). NeSmith, however, did not propose a method for predicting pile load capacity based on drilling resistance. Nor has he done so in his later publication (Nesmith Jr. and Nesmith, 2008). It should also be added that NeSmith's formulas and correlations apply only to a specific type of drill bit, „*ager pressure grouted displacement* (APGD) and to two types of piling rigs (Bauer BG25s and Cassagranda 220s).

The issue of screw displacement auger resistance and its prediction based on CPT soundings was studied earlier by the author of this article in Krasiński (2013, 2014). Moreover, a conception of the pile load capacity estimation based on the screwing resistance to drill augers was included in his habilitation thesis (Krasiński, 2013).

Some information about the problem of soil resistance to the screwing displacement auger and its connection with pile load capacity may also be found in the works of Kobrzyńska et al. (2018) and Trojnar & Siry (2019). However, these works do not provide proposals for forecasting the load capacity of piles based on the parameters of penetrating the forming tools.

In general, there are many publications and authorities on screw displacement piles. The French researchers Bustamante & Gianeselli (1998) were one of the first to propose methods for calculating the bearing capacity of displacement piles on the basis of CPT and pressuremetric test (PMT) results of the subsoil. Belgian researchers: Van Impe (2001), Maertens & Huybrechts (2003), Holeyman (2001), and Bottiau (2006) carried out extensive research to test various screw displacement pile technologies in field plots (including "Atlas," "Fundex," "Omega,"" "Olivier," "De Waal") in connection with various in situ tests of subsoil. American researchers

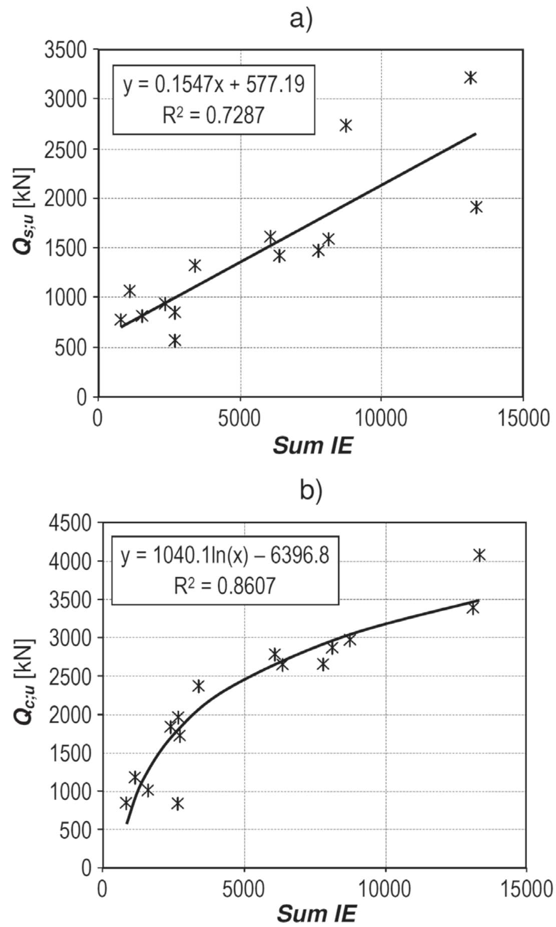


Figure 1: Correlations between summed drilling effort *SumIE* and ultimate bearing capacity of pile shaft (a) and of total pile (b), obtained by NeSmith (2003).

Basu & Prezzi (2010) and German scientists Pucker & Grabe (2012) conducted numerical simulations of the installation process of screw displacement piles in the ground and its impact on changes in soil parameters and pile load capacity. In addition to the author of this article, the topic of screwed displacement piles has also been dealt with by several Polish researchers: Gwizdała (2010), Konkol (2023), who analyzed the behavior of such piles on the basis of field tests or numerical simulations.

The abovementioned researchers generally omitted the topic of pile auger screwing resistances and the correlation between these resistances and the load capacity and stiffness of piles. It is difficult to explain why the discussed topic has not gained much interest among researchers so far. Admittedly, this is quite a complex subject.

The need to develop a method of estimating the load capacity of piles based on the screwing resistance of displacement drills is however reported in the industry —

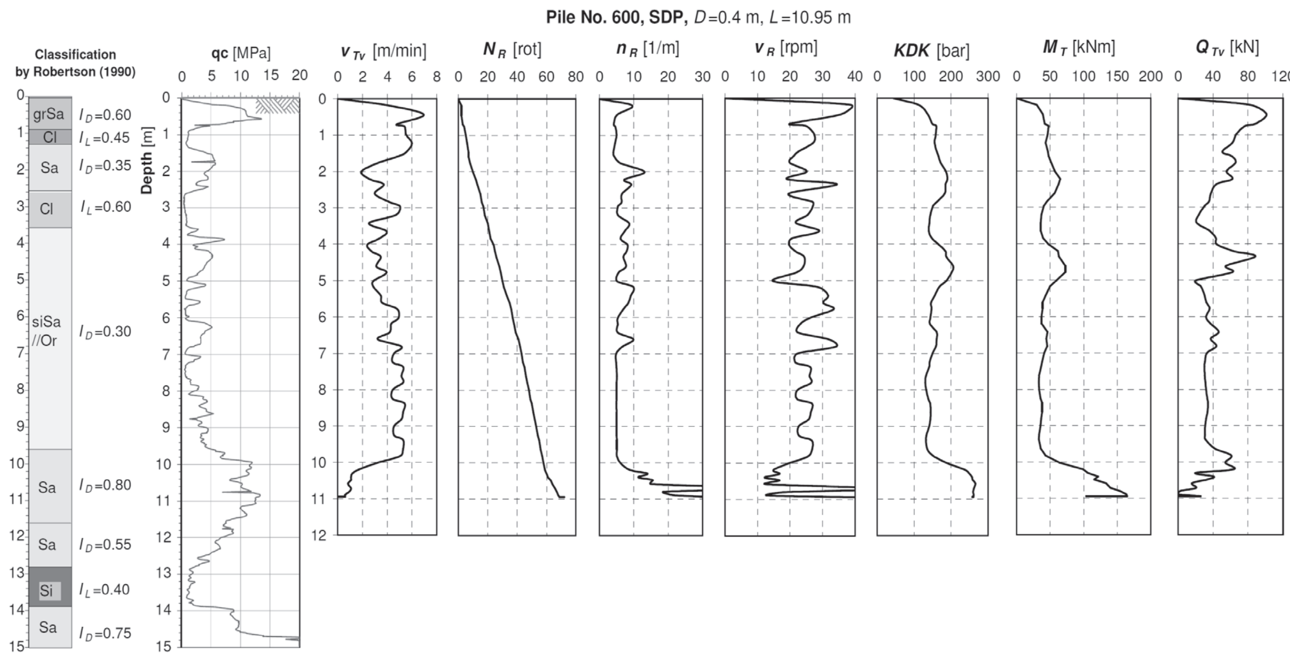


Figure 2: Selected graphs from the performance record of an example screw displacement pile.

pile contractors and designers. Moreover, the industry (mainly pile equipment producers) are undertaking many initiatives to solve the problem of high screwing resistance observed especially in noncohesive soils, and developing new constructions and shapes of pile augers to improve their efficiency.

It is possible to find a lot of publications on the correlation between screwing resistance and the load capacity of steel screwed piles, so-called helical piles, commonly used, for instance in the construction of offshore wind farms (e.g., Tsuha et al., 2010, Sakr, 2014, Saleem et al. 2020). However, the construction of such piles and the nature of their cooperation with the soil are completely different from those of the considered concrete screw displacement piles.

2 Auger resistances of forming screw displacement pile in ground

The process of screwing a displacement pile auger into the ground is a complex phenomenon. It is described by several parameters: torque M_T [kNm], number of rotations per depth unit n_R [1/m], penetration rate v_{Tv} [m/min], auger rotational speed v_R [1/min], and pressing force on auger Q_{Tv} [kN]. These parameters are primarily dependent on ground conditions and dimensions as well as the shape of the drilling auger. Selected graphs of auger screwing resistances from the performance record of an example pile drilling are shown in Fig. 2.

The mentioned parameters are also partly dependent on each other and on the actions of the pile drilling rig operator. For example, the greater penetration rate v_{Tv}, the greater the required torque M_T and pressing force Q_{Tv}. In turn, the greater pressing force Q_{Tv}, the greater torque M_T, and the smaller the number of rotations per depth unit n_R, and so on. In addition, hydraulic systems in drilling rigs are designed in such a way that with increasing rotational speed v_R, the value of maximum torque M_T decreases. Moreover, the drilling rig operator, depending on soil resistance, can decide on the drilling parameters, for example perform cyclic drilling by alternately increasing and decreasing the pressure force Q_{Tv} and the penetration rate v_{Tv}, thanks to which it is possible to achieve larger auger depths. Modern piling rigs are also equipped with devices that automatically adjust drilling parameters to the resistance encountered in the subsoil. The aforementioned factors undoubtedly complicate the physical description of the whole phenomenon and make it difficult to develop a good and universal method of estimating or predicting the load capacity of piles based on the auger screwing resistances.

3 Own field tests of the correlation between screwing resistance and the results of pile load tests

As stated in the previous section, predicting the bearing capacity of screw displacement piles based on the auger screwing resistance, in the author's opinion, can mainly be developed experimentally. Finding and developing such a method was therefore one of the goals of the "DPDT Auger" research project carried out by the author's team in 2019–2022 (Krasiński et. al., 2022a). As part of this project, 6 field research plots were organized at several locations in northern Poland, where a total of 24 screw displacement piles were constructed and tested. The geotechnical conditions were identified by means of sample drillings, CPTU (*Cone Penetration Test with water pressure U measurement*) and DMT (*DilatoMeter Test*) soundings and laboratory tests of soil samples. In most cases, the load-bearing layers were of saturated noncohesive soils, while in two plots there were also load-bearing layers of cohesive soils. In each plot, 4 test piles were made in addition to the anchor piles. During the production of all the piles, their installation parameters were measured and recorded in the pile execution reports. The piles were subjected to static load tests and gauged with vibrating wire extensometers, enabling the identification of pile shaft and base resistances. The main objective of the project was to test the prototype version of the displacement pile drilling tool (DPDT) auger (Fig. 3), which was patented in Poland in 2020 (Patent No. PL 235442 B1, [24]). For this reason, approximately half of the test and anchor piles were made with the DPDT or DPDT-S (*Shortened version*) augers and the other half, for comparison, with a traditional screw displacement pile (SDP) auger. All three tested drill augers are shown in Fig. 4.

In the DPDT auger, the disc helix, which is in the lower part of the SDP auger, has been replaced with a less prominent bar helix (of round or square section). The main reason for this was to reduce the torque M_T value when screwing the auger into the soil and to reduce or eliminate the loosening of noncohesive soil around the pile base. A side effect of the change is the slightly conical shape of the pile base which, however, according to research (Krasiński et al., 2022ab), did not reduce significantly the soil resistance under the pile base.

Comparative analyses showed that the DPDT auger required, in fact, lower torque M_T values but a higher number of rotations per depth unit n_R in comparison with the SDP auger. The middle section of the DPDT-S auger

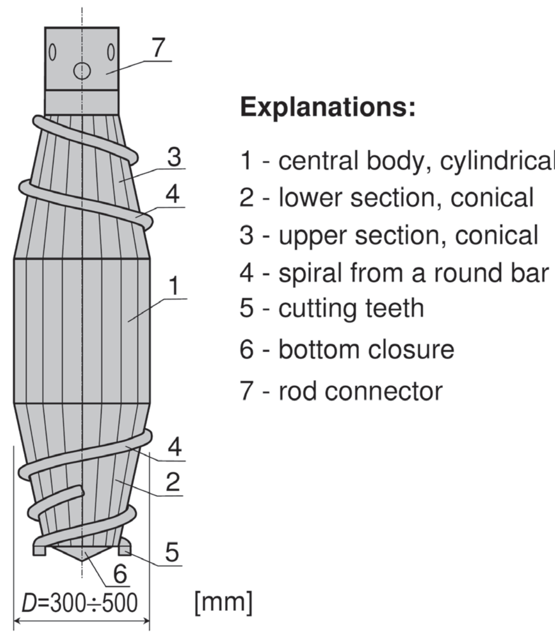


Figure 3: Scheme of prototype DPDT drill auger according to Patent No. PL 235442 B1, [24].

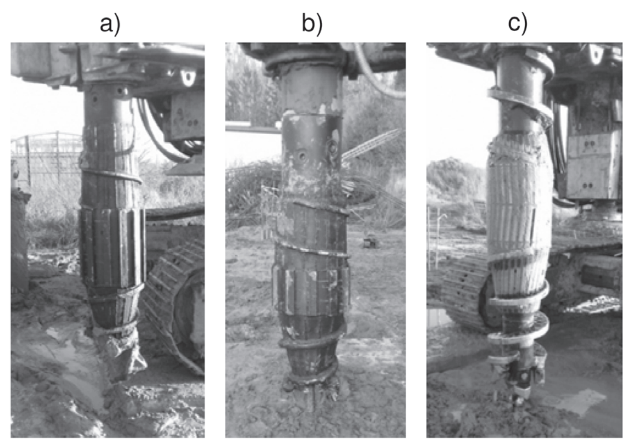


Figure 4: Displacement augers tested in the research project: a) DPDT b) DPDT-S, c) SDP

(Fig. 4b) is shortened by half in relation to the DPDT auger. Thanks to this, the value of the torque M_T is even more reduced.

This article presents the correlations between the auger screwing resistance and the load capacity of field-tested piles as well as their analyses. It was decided that two auger screwing parameters, torque M_T and the number of rotations per depth unit n_R would be the most reliable and representative factors in the discussed topic. It is known from practice that when the drill enters the strong soil layers, both of these parameters increase, and the energy or effort expended by the piling rig is the product of the multiplication of these values. Other drilling parameters like force Q_{Tv}, rotational speed v_R, and penetration rate v_{Tv} are auxiliary factors, largely related to and dependent on these two main parameters. Note that NeSmith (2003) made a similar assumption when he defined his *IE* parameter.

The fact that the DPDT auger required lower values of torque M_T, and a greater number of rotations per depth unit n_R than the SDP auger necessitated separate correlation analyses for both augers.

With regard to torque M_T, the author proposes the following simplification whereby its total value is the sum of component M_{Ts} resulting from soil friction on the auger side surface and the component M_{Tb} resulting from soil friction under auger bit (base). This assumption is schematically shown in Fig. 5, where the auger is expressed as a substitute cylinder, as in Krasiński (2014).

It would be most advantageous to measure the torque components M_{Ts} and M_{Tb} separately, and then look for correlations between M_{Ts} and the ultimate pile shaft resistance $Q_{s;ult}$ and the correlation between M_{Tb} and the ultimate pile base resistance $Q_{b;ult}$. However, this is difficult because the measuring system in the piling machine only records the total value of torque M_T. Separating the values of M_{Ts} and M_{Tb} would be approximately possible by stopping the vertical progress of the auger but continuing the rotation. There would be a decrease in torque M_T due to the reduction of M_{Tb} to practically zero, and thus the value of M_T would be approximately equal to M_{Ts}. However, performing such operations at a certain depth interval (e.g., every 0.5 m) while drilling a pile hole would be very troublesome and irrational. Nevertheless, such an action is possible and recommended at the very end of drilling, that is after reaching the desired depth of the auger. These operations were carried out during pile tests in the described research project.

When analyzing the schematic bit in Fig. 5, it should be considered whether unit resistances t_{Ts} can be compared to the frictional resistance q_s of the soil on the shaft of an axially loaded pile. A direct comparison cannot be made for several reasons. First, the resistances t_{Ts} are directed horizontally or slightly diagonally, while the resistances q_s are directed vertically. Secondly, the resistances t_{Ts} refer to the state of very large deformations (critical state), while in relation to resistances q_s we are interested in their maximum or limit values, which are mobilized at relatively small displacements. Thirdly, and probably most importantly, t_{Ts} resistance occurs when the soil is spread horizontally by the auger, generating much greater horizontal stresses in its vicinity (normal on the auger

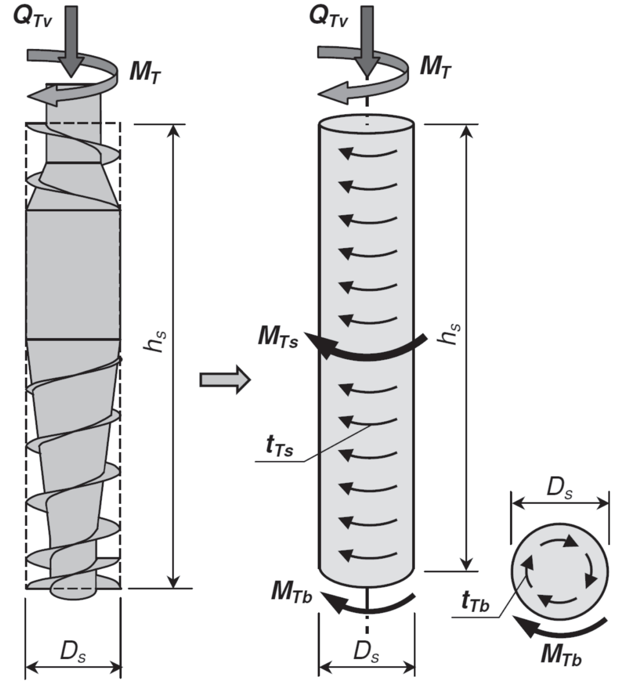
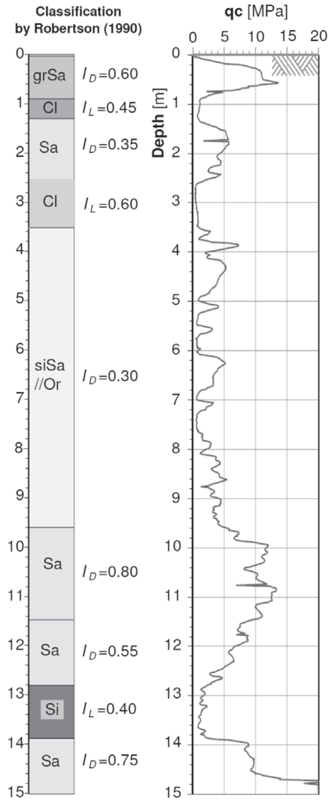


Figure 5: Auger and its simplified schematic representation (right) in the form of a cylinder (Krasiński, 2014).

sidewall) than after its unscrewing and the concreting of the pile (when stresses are much reduced). It is almost certain that t_{Ts} resistances reach much higher values than q_s resistances. In addition to this, there remains the problem of measuring the M_{Ts} values and determining the t_{Ts} resistances continuously during the auger screwing process.

Admittedly, numerical simulations of these phenomena have been undertaken by Basu & Prezzi (2010). Yet this author is of the opinion that the correlation between resistances t_{Ts} and q_s may still be found more accurately by empirical means.

Owing to the fact that the load-bearing capacity of a pile consists of shaft and base resistances, it was decided that the correlations between the auger screwing resistances and bearing capacities of the pile shaft and bearing capacities of the pile base should be considered separately. In the first case, the summed value of auger screwing effort $W_{T;s}$ (which may also be termed as screwing work or energy) in the load-bearing layers was assumed for the correlation with the limit resistance of the pile shaft $Q_{s;ult}$. In the second case, the value of auger screwing effort (work or energy) in the final phase of drilling, derived from soil resistance under the auger base (torque $M_{Tb;b}$), marked as $W_{T;b}$, was adopted for the correlation with the limit resistance of the pile base $Q_{b;ult}$.



Pile No. 600, SDP, L = 10.95 m					
z_i	N_R	n_R	M_T	$W_{T;s}$	$W_{T;b}$
[m]	[-]	[1/m]	[kNm]	[-]	[-]
0.0	0		0.0		
0.5	2	4.0	40.0		
1.0	5	6.0	45.0		
1.5	7	4.0	48.0		
2.0	10	6.0	52.0		
2.5	14	8.0	62.0		
3.0	17	6.0	50.0		
3.5	20	6.0	38.0		
4.0	23	6.0	42.0		
4.5	27	8.0	68.0		
5.0	30	6.0	70.0		
5.5	34	8.0	48.0		
6.0	37	6.0	40.0		
6.5	40	6.0	43.0		
7.0	43	6.0	46.0		
7.5	45	4.0	40.0		
8.0	48	5.0	34.0	85	
8.5	50	5.0	38.0	180	
9.0	53	5.0	38.0	275	
9.5	55	5.0	32.0	355	
10.0	58	6.0	48.0	499	
10.5	63	11.0	100.0	1049	
10.95	69	15.0	146.0	**2035**	**630**
10.95			104.0		
11.5					

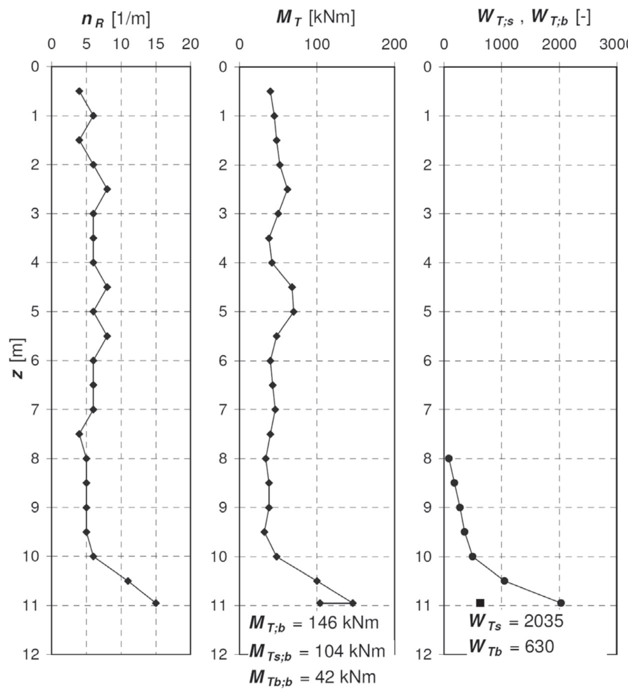


Figure 6: Diagrams of screwing parameters M_T and n_R as well as calculation of $W_{T;s}$ and $W_{T;b}$, for example, pile No. 600.

The summed value of screwing auger effort $W_{T;s}$ along the length of the load-bearing layers is calculated as:

$$W_{T;s} = \sum_i M_{T;i} \cdot n_{R;i} \cdot a_i \quad [-] \tag{4}$$

where: M_{Ti}—torque values M_T [kNm] in the load-bearing subsoil layers averaged at depths z_i increasing every 0.25 m or every 0.5 m, $n_{R;i}$—number of auger rotations per unit of depth [1/m], measured and averaged over depths z_i, a_i—depth increments z_i [m] ($a_i = z_i - z_{i\text{-}1}$ = 0,25 m or 0,5 m).

The value of screwing auger effort $W_{T;b}$ in the final phase of drilling is calculated as:

$$W_{T;b} = M_{Tb;b} \cdot n_{R;b} \quad [-] \tag{5}$$

where: $M_{Tb;b}$—component of torque $M_{T,b}$ [kNm] from soil resistance under the auger bit (base), measured in the final phase of auger screwing (at pile base level), $n_{R;b}$ —number of auger rotations per unit of depth [1/m], averaged for the last 0.5 m length of the screwing section.

The recommended number of rotations $n_{R;i}$ and $n_{R;b}$ in the above formulas should not exceed 15. This is due to the fact that sometimes the drilling rig operator, as mentioned earlier, may deliberately or involuntarily slow down or stop auger penetration, causing overestimation of the n_R value and consequently falsifying the calculated W_T value.

The value of the screwing torque $M_{Tb;b}$ component should be calculated as:

$$M_{Tb;b} = M_{T;b} - M_{Ts;b} \tag{6}$$

where: $M_{T;b}$—value of total torque measured and averaged over the final 0.5 m section of pile screwing, $M_{Ts;b}$—value of torque measured during auger rotation after stopping penetration at the end of screwing.

The values of $M_{T;b}$ and $M_{Ts;b}$ are read from the torque diagram (pile execution record), shown in Fig. 2 and Fig. 6. Figure 6 also shows the plots of n_R, M_T, $W_{T;s}$ and the calculated values of $W_{T;s}$ and $W_{T;b}$. Although the M_T, n_R, and a values are nominal, the $W_{T;s}$ $W_{T;b}$ values should be taken as non-nominated (dimensionless) for the purity of subsequent mathematical analysis. It is important, however, that the considered parameters M_T, n_R and a are taken in the specific units given above.

The level of starting the summation of $W_{T;s}$ values (top of load-bearing layers) should be determined on the basis

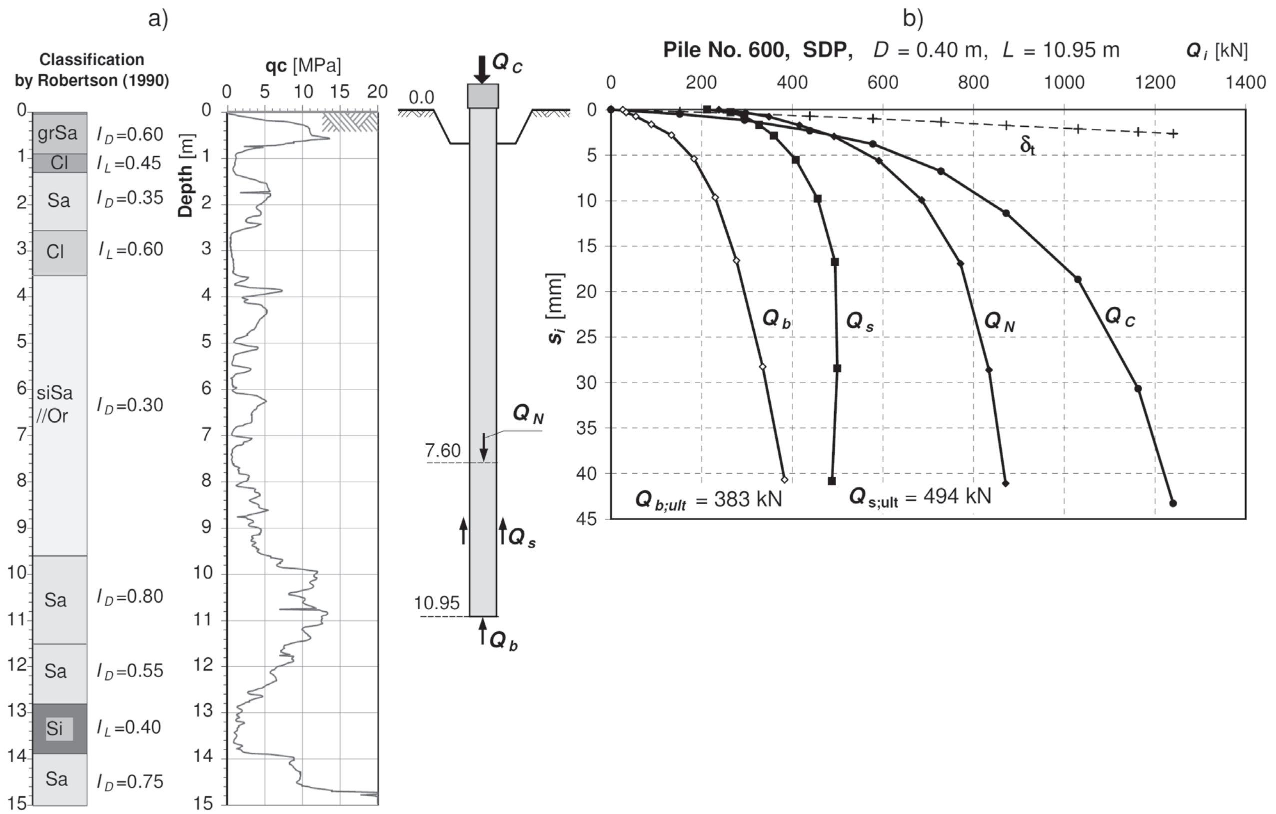


Figure 7: Example result of instrumented pile load test with specified limit load capacities of shaft $Q_{s;ult}$ and base $Q_{b;ult}$ (b) together with soil profile and cone resistance diagram (a).

of soil resistance measured during drilling (a noticeable increase in the value of M_T and potentially of n_R) or on the basis of subsoil tests (nearest CPT, DMT, or borehole). In Fig. 6, summation of $W_{T;s}$ values starts from depth z = 8.0 m (according to the CPT diagram). The depths z for individual piles tested in the research project varied and were based in all cases on CPT soundings.

The $W_{T;s}$ values for all the piles were correlated with the limit resistances of pile shafts $Q_{s;ult}$, and the $W_{T;b}$ values were correlated with the limit resistances of pile bases $Q_{b;ult}$. The loads acting on the pile shaft and the pile base were seperated, thanks to the instrumentation (extensometers) in the pile shaft. The values of limit resistances $Q_{s;ult}$ and $Q_{b;ult}$ were determined on the basis of Q-s diagrams from the pile tests using displacement criteria. For shaft resistance $Q_{s;ult}$, displacement $s_{s;ult}$ = 15 mm was assumed, and for the base resistance $Q_{b;ult}$—displacement $s_{b;ult}$ = 40 mm (10% of pile diameter D) was assumed. Example diagrams from the load test of pile No. 600 with the specified values of $Q_{s;ult}$ and $Q_{b;ult}$ are shown in Fig. 7.

Detailed results of correlations between the screwing auger resistances and load limit resistances for individual test piles in all the experimental plots can be found in the archival documentation of the “DPDT-Auger” research project (Krasiński et. al. 2022a).

Dependence graphs were prepared from correlations collected for all 24 research piles. After preliminary analysis, it was found that the best correlations were obtained for the values of relative (normalized) pile resistances, that is, divided by screwing resistances: $Q_{s;ult}/W_{T;s}$ and $Q_{b;ult}/W_{T;b}$. Graphs of these relative values as a function of representative screwing efforts $W_{T;s}$ and $W_{T;b}$ are shown in Fig. 8. Correlations for piles made with DPDT and SDP augers were so different that they had to be treated separately. In all cases, the obtained correlations were well approximated with power functions, see Fig. 8.

4 Use of obtained correlations to estimate load capacity and *Q-s* characteristics of piles

On the basis of the correlations presented in Fig. 8, relationships between the absolute values were derived, i.e. between the value of summed screwing effort $W_{T;s}$ and

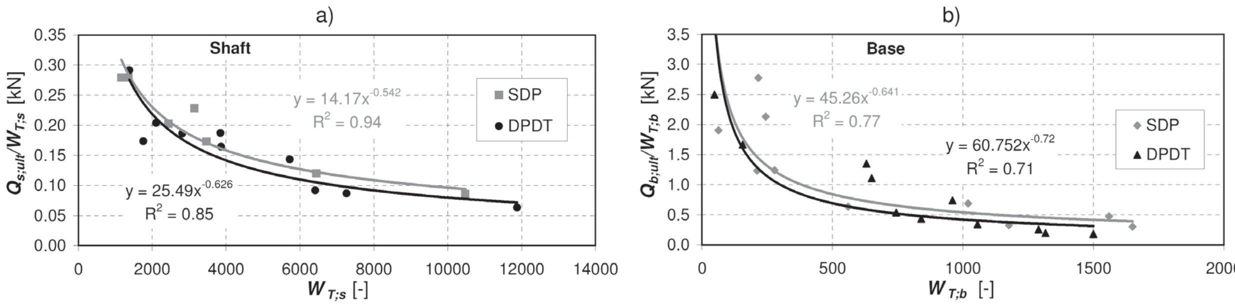


Figure 8: Relationships between representative auger screwing resistances and normalized limit resistances of piles, obtained from the tests, approximated by trend lines: a) for pile shaft, b) for pile base.

the limit resistance of the pile shaft $Q_{s;ult}$ and between the value of screwing effort $W_{T;b}$ in the final phase and the limit resistance of the pile base $Q_{b;ult}$. Taking into account the dispersion of measurement points and the values of the R^2 coefficients in Fig. 8, statistical processing of the results was carried out. This allowed the variation coefficients ν to be determined: νs = 0.08 in relation to the shaft resistance and νb = 0.18 in relation to the base resistance. The values of coefficients νs and νb were averaged for SDP and DPDT augers due to their similarity in cases of both augers. In the case of dependencies concerning pile base resistances ($Q_{b;ult}$ from $W_{T;b}$), a slight correction was made by dividing these dependencies into two ranges (for $W_{T;b} \leq 500$ and for $W_{T;b} > 500$) so as to not to overestimate base resistance values $Q_{b;ult}$ for low values of $W_{T;b}$ (below 500).

The derived relationships between the absolute quantities $Q_{s;ult}$ and $W_{T;s}$, and $Q_{b;ult}$ and $W_{T;b}$ are expressed as follows:

a) In relation to piles made with the SDP auger:

- ultimate shaft resistance: $Q_{s;ult} = 14.2 \cdot (W_{T;s})^{0.46}$ [kN] (7)

- ultimate base resistance:

- for $W_{T;b}$, ≤ 500 - $Q_{b;ult} = 9.55 \cdot (W_{T;b})^{0.61}$ [kN] (8a)

- for $W_{T;b}$, > 500 - $Q_{b;ult} = 45.3 \cdot (W_{T;b})^{0.36}$ [kN] (8b)

b) In relation to piles made with the DPDT auger:

- ultimate shaft resistance: $Q_{s;ult} = 25.5 \cdot (W_{T;s})^{0.37}$ [kN](9)

- ultimate base resistance:

- for $W_{T;b}$, ≤ 500 - $Q_{b;ult} = 13.7 \cdot (W_{T;b})^{0.52}$ [kN] (10a)

- for $W_{T;b}$, > 500 - $Q_{b;ult} = 60.8 \cdot (W_{T;b})^{0.28}$ [kN] (10b)

The above relationships are presented in the form of diagrams in Fig. 9. It can be seen that the dependencies have nonlinear courses on account of the fact that the increase in values of ultimate pile resistances $Q_{s;ult}$ and $Q_{b;ult}$ is gradually lessened with the increase of screwing resistance, which is confirmed by observations from practice and the general nature of screw displacement pile performance (in that their load capacities do not increase proportionally to the increase in the mechanical parameters of the subsoil).

The total value of pile ultimate resistance will next be the sum of shaft and base resistances:

$$Q_{c;ult} = Q_{s;ult} + Q_{b;ult} \tag{11}$$

The values of $Q_{s;ult}$, $Q_{b;ult}$ and $Q_{c;ult}$ in formulas (7) to (11) correspond to the pile-bearing capacities considered in EC7 [25], i.e.:

$$R_{s;cal} = Q_{s;ult} \;, \quad R_{b;cal} = Q_{b;ult} \quad \text{and} \quad R_{c;cal} = Q_{c;ult} \tag{12}$$

Next, recommendations and coefficients given in EC7 should be used to determine the characteristic capacities $R_{s;k}$, $R_{b;k}$, $R_{c;k}$ and the design pile capacities $R_{s;d}$, $R_{b;d}$, and $R_{c;}$.

The developed method can next be used to approximate the *Q-s* characteristics of piles. For this purpose, the values of ultimate pile resistances $Q_{s;ult}$, $Q_{b;ult}$, obtained from the screwing auger resistances, may be used in calculating the *Q-s* characteristics of piles using the transfer function equations developed in the same "DPDT-Auger" research project (Krasiński et al., 2022a, 2023):

a) For shaft resistance: $Q_s(s_s) = Q_{s;ult} \cdot \left(\frac{s_s}{15.0}\right)^{0.28}$ [kN] (13)

b) For base resistance: $Q_b(s_b) = Q_{b;ult} \cdot \left(\frac{s_b}{40.0}\right)^{0.50}$ [kN] (14)

where: s_s – value of pile shaft vertical displacement [mm], averaged in downer bearing layers, s_b – value of pile base vertical displacement [mm].

Assuming an infinitely rigid pile shaft, the values of s_s and s_b are equal ($s_s = s_b$).

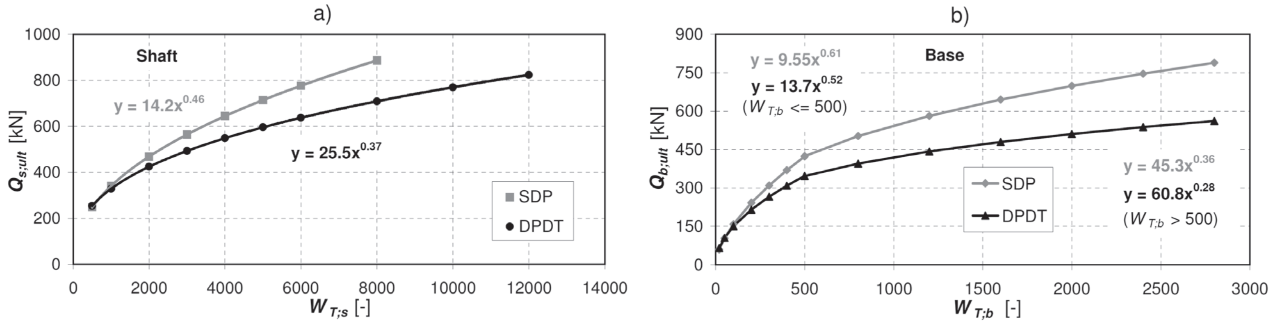


Figure 9: Derived relationships between pile load limit resistances $Q_{s;ult}$ (a) and $Q_{b;ult}$ (b) and representative screwing resistances $W_{T;s}$ (a) and $W_{T;b}$ (b) separately for SDP and DPDT drill augers.

5 Calculation example

The calculation example was carried out for the case of pile No. 600 made by using the SDP auger. Data on screwing resistances are presented in Fig. 6 above, where the representative values of screwing resistances (efforts) are: $W_{T;s}$ = 2035 and $W_{T;b}$ = 630.

Using formulas (4) and (5b), the following values of pile ultimate resistances were calculated:

- shaft ultimate resistance:

$$Q_{s;ult} = 14.2 \cdot (2035)^{0.46} = 472.0 \text{ kN}$$

- base ultimate resistance:

$$Q_{b;ult} = 45.3 \cdot (630)^{0.36} = 461.0 \text{ kN}$$

- total ultimate resistance:

$$Q_{c;ult} = 472.0 + 461.0 = 933.0 \text{ kN}$$

From the actual pile tests (the results of which are presented in Fig. 7) the obtained values of ultimate resistances were, respectively: $Q_{s;ult}$ = 494 kN, $Q_{b;ult}$ = 383 kN and $Q_{c;ult}$ = 494 + 383 = 877 kN. Thus, the ultimate resistance values of the SDP pile, estimated on the basis of auger screwing resistances approximately correspond to the real values. A slightly higher ultimate value of the estimated base resistance ($Q_{b;ult}$ = 461 kN) in relation to the real resistance value ($Q_{b;ult}$ = 383 kN) may result from a weaker silt layer (Si) under the base, at a depth of approximately 13 to 14 m (as in the CPT chart in Figs. 6 and 7). The presence of this layer could not be identified by the method based on the pile auger resistance. The inability to capture weaker layers under the pile base is in a certain sense a shortcoming of the developed method.

Expressions for the *Q-s* characteristics of the example pile were obtained as follows:

a) For shaft resistance: $Q_s(s_s) = 472 \cdot \left(\frac{s_s}{15.0}\right)^{0.28}$ [kN]

b) For base resistance: $Q_b(s_b) = 461 \cdot \left(\frac{s_b}{40.0}\right)^{0.50}$ [kN]

The calculated numerical values of the *Q-s* characteristics and their graphs, compared with the graphs from real tests, are shown in Fig. 10.

The result of estimating pile-bearing capacity and *Q-s* characteristics in the considered example may be assessed positively, although it should be noted that the accuracy of proposed method can be estimated at about ±20%.

6 Conclusions

The conducted tests and analyses have shown that there is quite regular correlation between the measured screwing resistance of displacement auger and the load-bearing capacity of piles. For this correlation, parameters of auger screwing resistance should be used in the form of torque value M_T and the number of auger rotations per unit of its penetration n_R. The observed correlations can be described using mathematical functions, which would be slightly different for SDP auger piles and prototype DPDT (or DPDT-S) auger piles.

The derived correlations make possible the development of an empirical method for estimating the load-bearing capacities and *Q-s* characteristics of screw displacement piles on the basis of measurements of auger screwing resistances. The proposed method is ±20% accurate. This accuracy can be improved by additionally calibrating the method on the basis of obligatory static pile load tests on the given construction site, preferably using instrumented piles.

In order to increase the reliability of the proposed method, the piling machine operator should be instructed to drill the piles systemically, in a uniform manner for all piles, and after stopping at the target depth, perform 2–3 idle rotations of the auger to measure the value of the $M_{Ts;b}$ component in the total torque $M_{T;b}$ value.

Table of calculation

s [mm]	Q_s [kN]	Q_b [kN]	Q_N [kN]	δ_t [mm]	$s+\delta_t$ [mm]
0.0	0.0	0.0	0.0	0.00	0.00
0.5	182.1	51.5	233.7	0.48	0.98
1.0	221.1	72.9	294.0	0.61	1.61
2.0	268.5	103.1	371.6	0.79	2.79
3.0	300.8	126.3	427.0	0.92	3.92
4.0	326.0	145.8	471.8	1.03	5.03
5.0	347.0	163.0	510.0	1.12	6.12
7.0	381.3	192.9	574.1	1.28	8.28
9.0	409.1	218.7	627.8	1.41	10.41
12.0	443.4	252.5	695.9	1.58	13.58
15.0	472.0	282.3	754.3	1.73	16.73
20.0	472.0	326.0	798.0	1.88	21.88
25.0	472.0	364.5	836.5	2.01	27.01
30.0	472.0	399.2	871.2	2.12	32.12
35.0	472.0	431.2	903.2	2.23	37.23
40.0	472.0	461.0	933.0	2.33	42.33

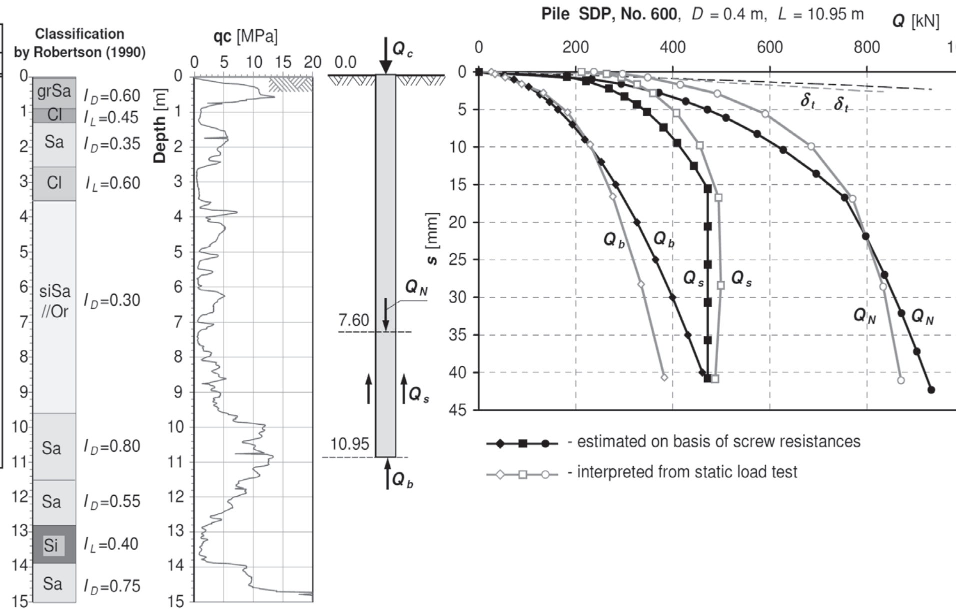


Figure 10: *Q-s* characteristics of the SDP pile No. 600, estimated on the basis of the auger screwing resistance compared with result of the real test.

The proposed method applies to SDP and DPDT (DPDT-S) augers with a diameter of D_s = 0.40 m and shapes similar to those shown in Fig. 4. The method can also be used for augers with other diameters, but only after appropriate recalculations of the values of both the torque M_T and the ultimate resistances of the pile $Q_{s;ult}$ and $Q_{b;ult}$ and calibrating them with the results of static tests with real piles.

Obtaining different correlations for DPDT and SDP augers indicates that separate methods should also be developed for other auger types and shapes (e.g., “Omega,” CMC, “DeWaal,” “Atlas,” etc.), but using similar assumptions and procedures to those proposed in the article.

The important practical value of the developed method should be emphasized. It can be used, for example, for control of ongoing execution of screw displacement piles on construction sites in terms of obtaining the required load-bearing capacity of all the piles, as in the case of driven piles, as well as for as-built assessment of pile-bearing capacity, useful, among others, in acceptance procedures.

The presented method is the first version and relatively recently developed by the author on the basis of researches carried out by the “DPDT-Auger” project team. The method is universal in relation to the soil types (cohesive as well as noncohesive). In the future, it will still be subject to verification by the results of subsequent pile load tests and, on their basis, it will probably undergo corrections or modifications and maybe ones that will require a separate approach for cohesive and noncohesive soils.

Acknowledgments: The described test and analyses results of augers and piles were obtained from research works conducted in the “DPDT Auger” research project, financially supported by the Polish National Centre for Research and Development (project No. POIR 4.1.4. 0124/18, “Development of a method and tools for the installation of screw displacement columns/piles in various ground conditions in Poland, together with the preparation of a methodology for the design and acceptance of works”). The project was carried out by consortium of Gdansk University of Technology and the Polish geotechnical company Budokop Geotechnika Sp. z o.o.

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