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RESULTS OF THE "DPDT-AUGER" RESEARCH PROJECT ON SCREW DISPLACEMENT PILES

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Abstract
The main objective of the "DPDT-Auger" research project was to test the prototype DPDT auger for forming screw displacement piles in the ground (patented in Poland in 2020). An additional aim was to develop design methods and rules for the making of such piles. The augers and piles were first tested on a model scale, and then more extensively in the real scale on experimental field plots. The results found the overall functionality of the DPDT auger to be good, and in several aspects better than that of the SDP auger. The load-bearing capacities and *Q-s* characteristics of piles made with both augers were considered comparable. All the conducted tests and their derived dependencies together with the results of in situ subsoil tests allowed for the development of empirical calculation methods and prognostic procedures, useful for designing and producing piles with DPDT and SDP augers. FEM numerical simulation rules for the considered piles were also developed, verified and calibrated by the results of real pile tests. This article describes only the most important final results of the research project but not the detailed results of the numerous tests and analyses that were carried out. Also omitted are the results of model tests and numerical simulations, as well as the implementation and acceptance recommendations, as they have already been or will be the subject of separate publications.

Keywords: **Screw displacement pile; Pile auger; Pile load capacity; Soil resistance during pile formation; Piles calculation.**

1. INTRODUCTION

In 2019–2022, a consortium of the Gdańsk University of Technology and the geotechnical contractor Budokop Geotechnika Sp. z o. o. (Leader) carried out the "DPDT-Auger" research project on screw displacement piles. An inspiration to launch the project was the development of a new prototype version of pile auger invented at the Gdańsk University of Technology by the main author of this article. The DPDT (*Displacement Pile Drilling Tool*) was patented in Poland as PL 235442 B1 [1] in 2020.

Screw displacement piles and columns are currently one of the most popular technologies for piling and soil improvement on account of their technical and economic advantages. However, their drawback is the high resistance encountered when screwing the auger into the ground. These resistances occur mainly in non-cohesive soils, making it difficult to obtain longer piles with deeper embedment in load-bearing layers and necessitating the use of high rotational power drilling rigs. In cohesive soils, on the other hand, resistances have lower values, but cause the generation of excessive pore water pressure and degradation of soil structure (mainly cohesion), which may result in the reduction of pile load capacity.

The prototype version of the DPDT auger was supposed to generate lower screwing resistance in non-cohesive soils and less disturbance to cohesive soil structure. These assumptions were initially checked and confirmed in model tests, even before the auger was patented. This is why the auger required verification on the natural scale (in the field conditions) and in terms of pile load capacities and *Q-s* characteristics. An additional advantage is the simplicity of the auger construction, Fig. 1, reducing the costs of its production and regeneration.

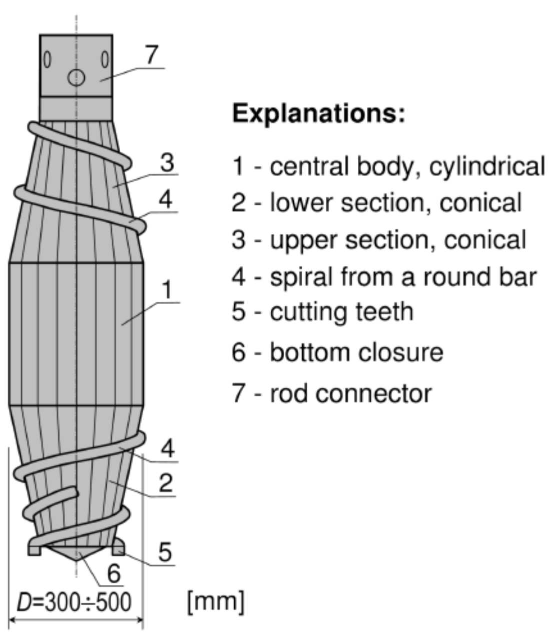


Figure 1.
Construction of the prototype DPDT drill auger according to Patent No. PL 235442 B1, [1]

In the research project, a prototype version of DPDT auger was tested in comparison with other displacement augers commonly used in practice, mainly SDP (*Screw Displacement Pile*). The project consisted of 7 stages. In Stage 1, augers and piles were tested on a model scale, as described, among others, in [2]. In Stages 2, 3 and 4, full-scale tests were performed on experimental field plots. Auger and pile tests were combined with in-situ and laboratory subsoil tests. Other project tasks (Stages 5, 6 and 7) included analysis of obtained test results and developing reliable methods for calculating and predicting bearing capacity, settlement characteristics and performance parameters, including FEM numerical methods (omitted in this paper but described in [3]) and the development of recommendations for control and acceptance of piling works.

This article focuses mainly on presenting the final results of the project, observed correlations and regularities as well as empirical methods developed for calculating and predicting the bearing capacity, settlement characteristics *Q-s* and the performance parameters of screw displacement piles.

2. FIELD TESTS OF AUGERS AND PILES

In the field investigations, 6 experimental plots were organized in several locations in northern Poland. In total, over 80 screw displacement piles were made and tested by Budokop Geotechnika. These included 24 research piles and the rest were anchor piles. The geotechnical subsoil structure on the plots was determined using exploratory boreholes, CPTU [4] and DMT [5] soundings and laboratory tests of soil samples (Project Stage 3). Stage 2 was devoted to testing the DPDT and DPDT-S augers (shortened length version) and traditional SDP auger in terms of resistance during penetration into the ground. For comparative purposes, approximately one half of the test and anchor piles were made with DPDT and DPDT-S augers and the other half with the SDP auger. Four test piles were made in each plot, which after obtaining full concrete strength, were subjected to static load tests (Stage 4). All three of the tested augers had a diameter of $D = 0.40$ m, Fig. 2.

Complete results of full-scale tests on screwing resistance are included in the Report [6] and partly in [7]. A comparative example of the resistances of DPDT, DPDT-S and SDP augers from one of the test plots (No. 2) is shown in the form of graphs in Fig. 3, where the torque is M_T, the unit number of rotations is n_R and the drilling times is t_D. In the context of screwing resistance, field test results generally confirmed the results of model tests performed in Stage 1, described in [2]. When screwing into the ground, prototype DPDT and DPDT-S augers generated lower values of torques M_T, while higher unit rotations number n_R than the corresponding SDP auger. The differences described above became more visible when augers reached the lower, load-bearing subsoil layers, where

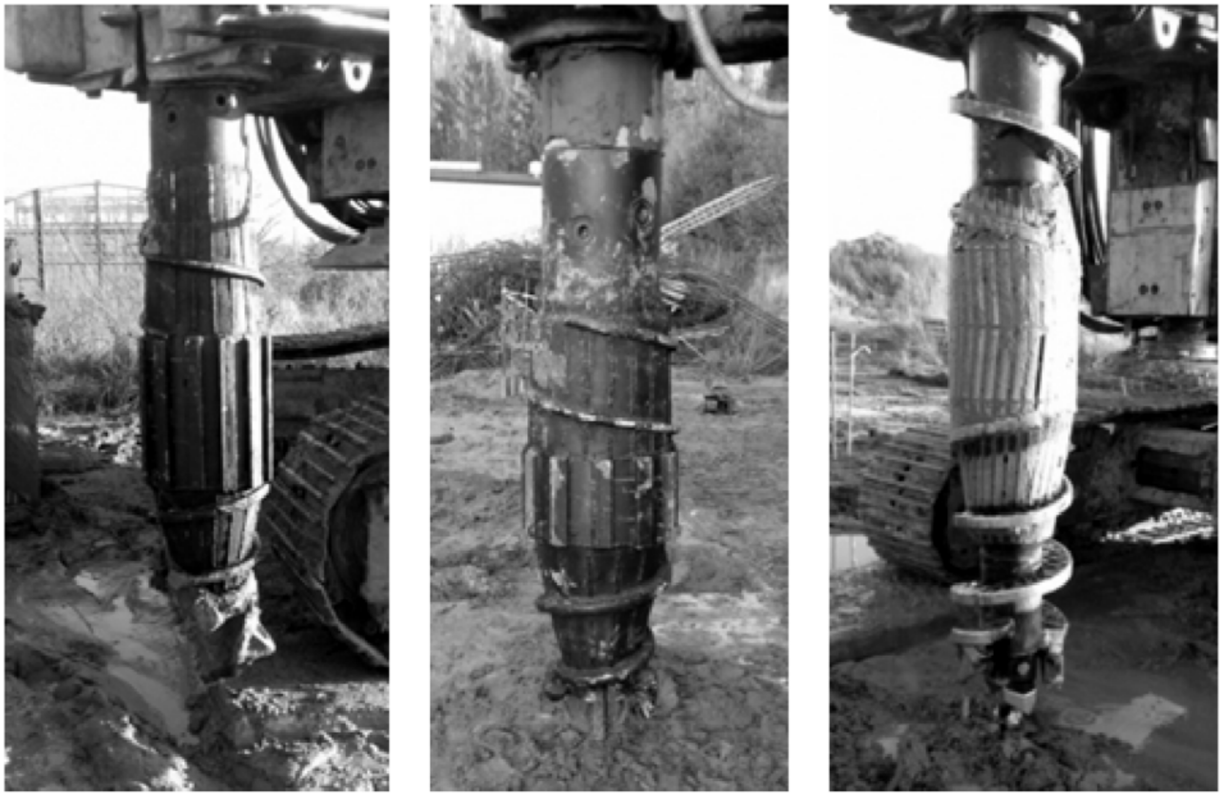


Figure 2.
Displacement pile augers tested in the research project: a) DPDT auger, b) DPDT-S auger (shortened length version), c) SDP auger, [6]

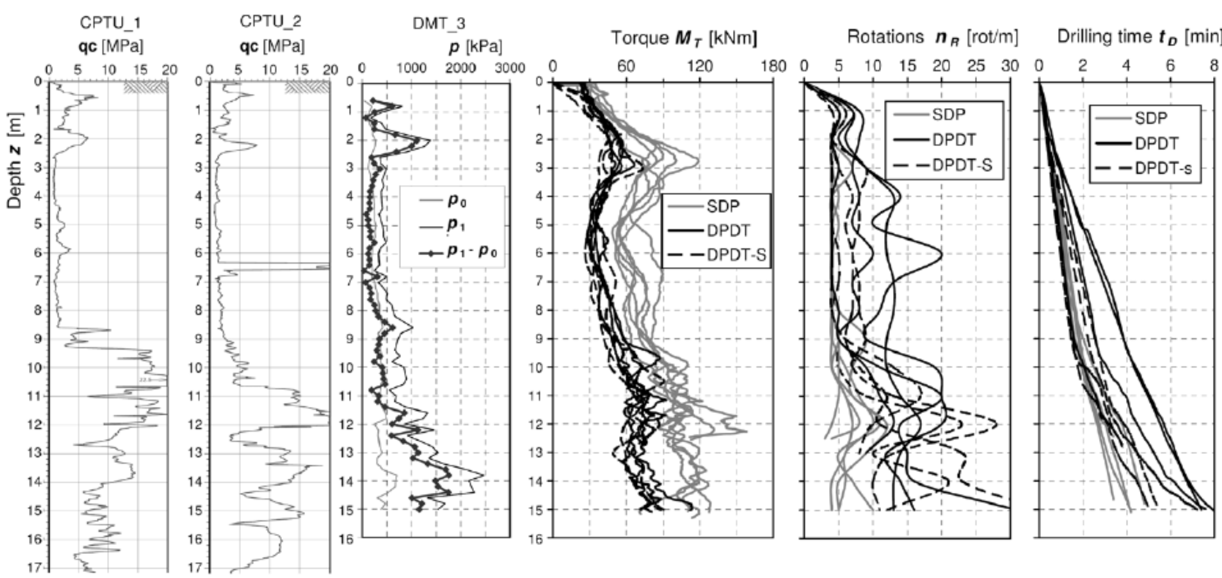


Figure 3.
A graphical comparison of the screwing parameters of DPDT, DPDT-S and SDP augers (Test plot No. 2)

the piles were ended. The increased number of generated rotations n_R of DPDT and DPDT-S augers causes an extension of pile installation time by 30–40% when compared to SDP auger.

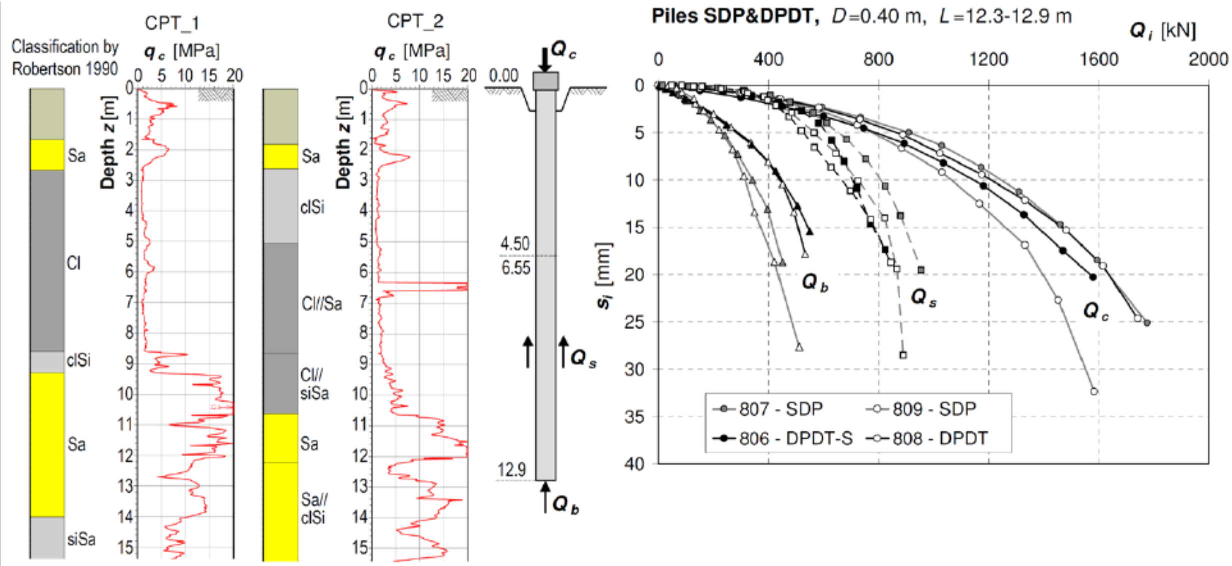


Figure 4.
Comparative results of pile load tests from experimental plot No. 2, [6]

Nevertheless, the the performance of prototype auger was assessed positively due to the reduced M_T value. This advantage is the most important, as it enables achieving greater penetration depths and thus allows for making piles of greater lengths and greater load capacities. It also gives a greater guarantee of effective pile installation in various ground conditions.

Field static pile load tests were the subject of Stage 4. Tests were carried out with additional pile instrumentation, using vibrating wire extensometers. The aim was to determine the bearing capacity and *Q-s* characteristics with separate identification of the pile shaft and pile base resistances. Examples of comparative results of static pile tests conducted in experimental plot No. 2 are shown in Fig. 4. Both, these results and other experimental plots showed that DPDT (DPDT-S) and SDP piles are characterized by similar soil interaction parameters (capacity and *Q-s* characteristics).

3. CORRELATIONS OBTAINED FROM FIELD RESEARCH AND DEVELOPED CALCULATION METHODS

The search for and determination of various correlations between the field test results of subsoil, augers and piles was the subject of Stage 5. This article describes the correlations between in the situ subsoil tests and pile bearing capacities and between the in situ subsoil tests and pile screwing resistance. Based on these correlations, computational and prognostic empirical methods for piles made with DPDT and SDP augers were also developed and presented. Due to their extensiveness and complexity, the correlations between the screwing pile auger resistances, the load capacities and the *Q-s* characteristics, as well as the corresponding calculation methods, have been described in a separate publication [8].

3.1. Correlations between CPT soundings and piles bearing capacity

Values of soil unit resistances along the pile shaft t_s [kPa] and under the base q_b [kPa] were determined from pile load tests. The aim was to find a correlation between the mentioned pile resistances and the resistance of the CPT cone q_c. For this purpose, the representative (equivalent) cone resistances q_{cs} and q_{cb} were calculated according to the scheme shown in Fig. 5 (similar to the one proposed in [9, 10]). The values of q_{cs} and q_{cb} were calculated as the harmonic mean of the q_c values read from the zones corresponding to the shaft and base of a given pile, with additional consideration of weighting factors (formulas in Fig. 5). In the case of layered soils (cohesionless with cohesive), the q_{cs} values should be calculated separately for each layer (for more, see [6]).

Fig. 6 shows the correlation results with regard to the ultimate $t_{s;ult}$ and $q_{b;ult}$ resistances, which were determined by displacement criteria – for the shaft resistance $s_{s;ult}$ = 15 mm, and for the base resistance

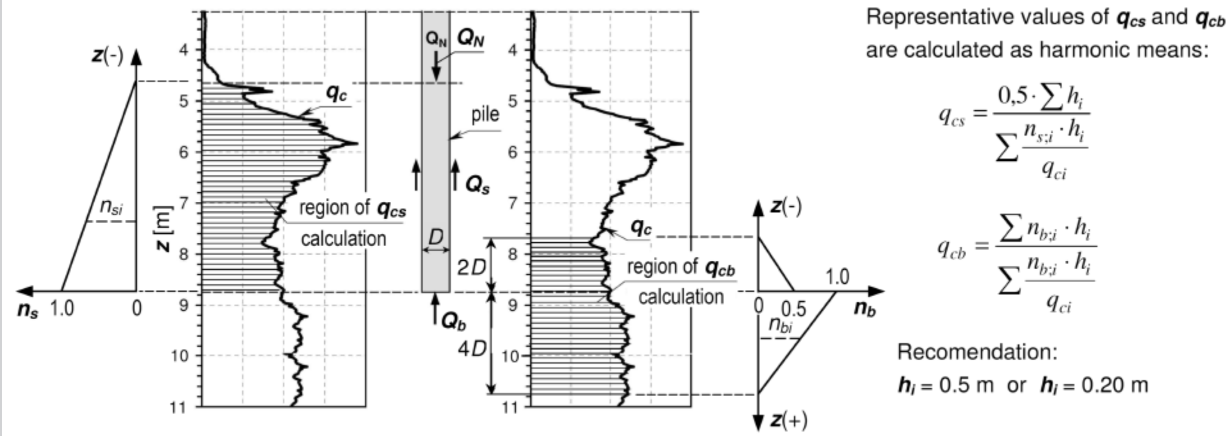


Figure 5.
Scheme for determining representative values of cone resistances q_cs and q_{cb}

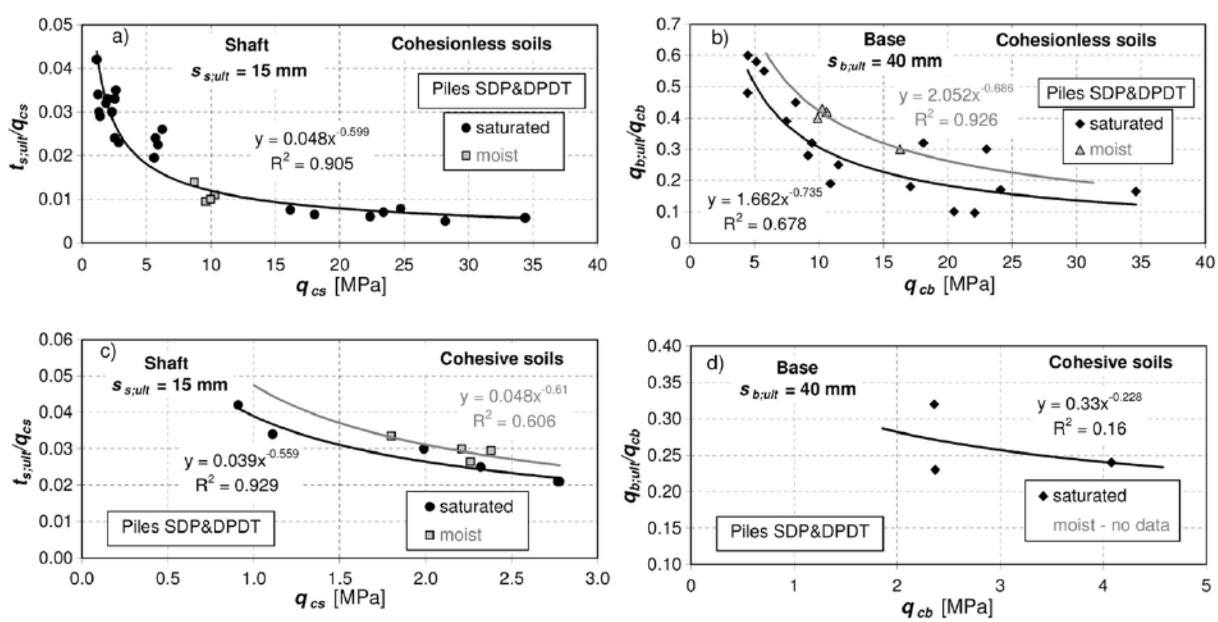


Figure 6.
Correlations between ultimate unit resistances of DPDT and SDP piles and representative CPT(U) cone resistances for cohesionless and cohesive soils

$s_{s;ult}$ = 40 mm (10 % of pile diameter D). The above correlations could be unified for piles made by using both DPDT and SDP auger types on account of their closeness, but had to be separated into cohesionless and cohesive soils, and into saturated and moist (unsaturated) soils. Very little research data was obtained in the case of base resistances for cohesive soils, hence the correlation for $q_{b;ult}/q_{cb}$ in Fig. 6d is very approximate and subject to high uncertainty (R^2 = 0.16). The discussed correlation was also described with the power function, mainly due to the preservation of the same description as in the other correlations shown in Fig. 6. In the future, this correlation will still need to be verified with further research results.

Empirical formulas were created to calculate the ultimate unit resistances $t_{s;ult}$ and $q_{b;ult}$ of the soil based on representative cone resistances q_{cs} and q_{cb}. These formulas, which are listed in Tab. 1, can be used for an engineering purposes to calculate the pile load capacity in accordance with EC7 recommendations [11].

Table 1.
List of formulas for calculating ultimate resistances $t_{s;ult}$ and $q_{b;ult}$ of the soil around DPDT and SDP piles, based on CPT(U) soundings

Soil type	Pile shaft $t_{s;ult}$ [kPa]	Pile base $q_{b;ult}$ [kPa]	Scope of use
Cohesionless saturated	$t_{s;ult} = 85 \cdot \left(\frac{q_{cs}}{q_{ref}}\right)^{0.18}$	$q_{b;ult} = 1660 \cdot \left(\frac{q_{cb}}{q_{ref}}\right)^{0.27}$	q_{cs} = 5÷35 MPa q_{cb} = 5÷35 MPa incl. organ. ≤ 2%
Cohesionless unsaturated		$q_{b;ult} = 2050 \cdot \left(\frac{q_{cb}}{q_{ref}}\right)^{0.30}$	q_{cs} = 5÷35 MPa q_{cb} = 5÷35 MPa incl. organ. ≤ 2%
Cohesive saturated	$t_{s;ult} = 39 \cdot \left(\frac{q_{cs}}{q_{ref}}\right)^{0.44}$	$q_{b;ult} = 330 \cdot \left(\frac{q_{cb}}{q_{ref}}\right)^{0.78}$	q_{cs} = 1÷4 MPa q_{cb} = 1÷4 MPa incl. organ. ≤ 2%
Cohesive unsaturated	$t_{s;ult} = 48 \cdot \left(\frac{q_{cs}}{q_{ref}}\right)^{0.39}$	No data (A formula for cohesive saturated can be used)	q_{cs} = 1÷4 MPa q_{cb} = 1÷4 MPa incl. organ. ≤ 2%
Comments: 1) values of $q_{cs;i}$ and q_{cb} should be given in MPa 2) reference stress should be taken as q_{ref} = 1 MPa			

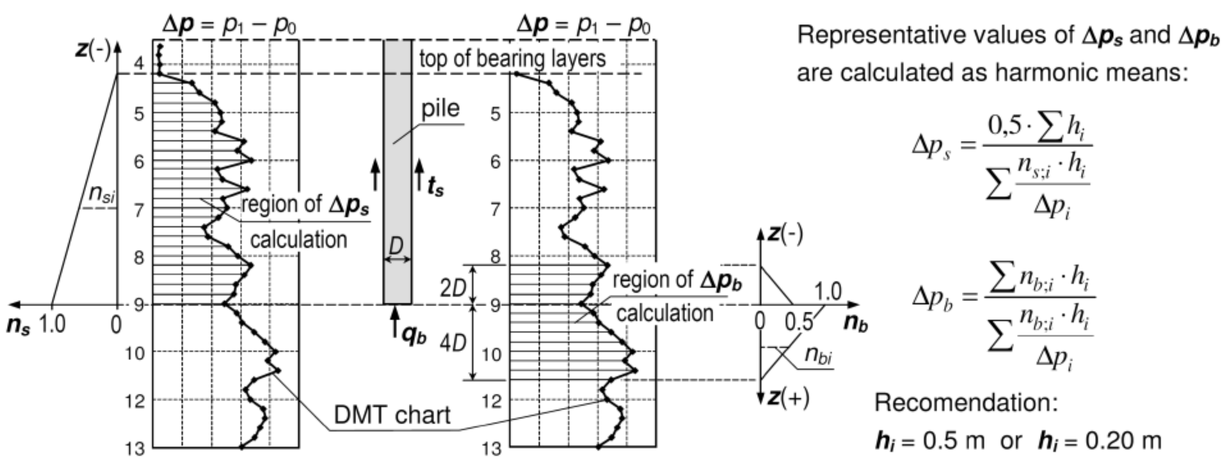


Figure 7.
Scheme for determining representative values of DMT membrane resistances p_s and p_b

3.2. Correlations between DMT soundings and piles bearing capacity

Similar correlations as those described in section 3.1. but between the soil resistances t_s and q_b and the resistances measured on the membrane of the Marchetti dilatometer (DMT, [4]) were also analysed. In this case, representative parameter Δp [kPa] was adopted, calculated as the difference between resistances p_1 and p_0 measured directly on the dilatometer membrane during soil testing ($\Delta p = p_1 - p_0$). As for cone resistance q_c, a scheme for calculating the representative Δp_s and Δp_b values presented in Fig. 7 was adopted. These values should also be calculated as harmonic means and in the case of a stratified subsoil, separately for cohesionless and cohesive soil layers (for more, see [6]).

The results of the correlation between the ultimate unit resistances of pile $t_{s;ult}$ and $q_{b;ult}$ and the representative resistances Δp_s and Δp_b of the dilatometer membrane are shown in Fig. 8. They turned out to be very similar to those presented in Fig. 6, which refers to the resistances of a CPT cone q_c. Again, these correlations could be unified for piles made with DPDT and SDP augers, but they have to be divided into cohesionless and cohesive soils as well as saturated and moist (unsaturated) soils.

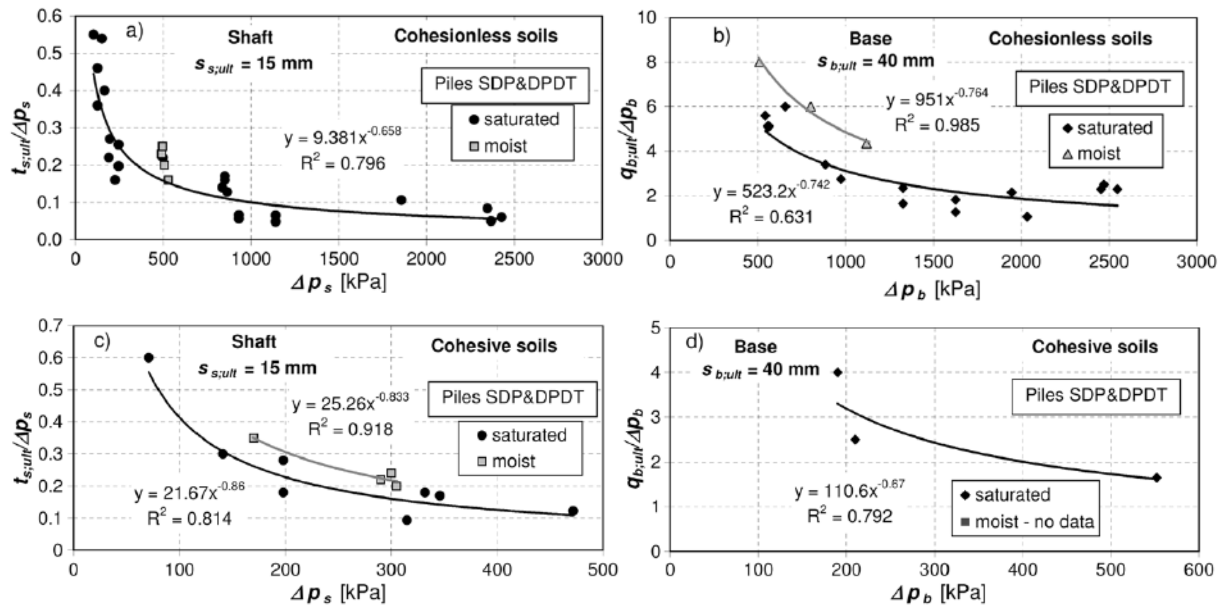


Figure 8.
Correlations of ultimate unit resistances around DPDT and SDP piles and representative DMT membrane resistances

Table 2.
List of formulas for calculating ultimate resistances $t_{s;ult}$ and $q_{b;ult}$ of DPDT and SDP piles based on DMT soundings

Soil type	Pile shaft $t_{s;ult}$ [kPa]	Pile base $q_{b;ult}$ [kPa]	Scope of use
Cohesionless saturated	$t_{s;ult} = 11.75 \cdot \left(\frac{\Delta p_s}{p_{ref}}\right)^{0.31}$	$q_{b;ult} = 525 \cdot \left(\frac{\Delta p_b}{p_{ref}}\right)^{0.26}$	Δp_s = 400÷2500 kPa Δp_b = 500÷3000 kPa incl. organ. ≤ 2%
Cohesionless unsaturated		$q_{b;ult} = 950 \cdot \left(\frac{\Delta p_b}{p_{ref}}\right)^{0.24}$	Δp_s = 400÷2500 kPa Δp_b = 600÷3000 kPa incl. Organ. ≤ 2%
Cohesive saturated	$t_{s;ult} = 22 \cdot \left(\frac{\Delta p_s}{p_{ref}}\right)^{0.14}$	$q_{b;ult} = 110 \cdot \left(\frac{\Delta p_b}{p_{ref}}\right)^{0.37}$	Δp_s = 100÷600 kPa Δp_b = 100÷1000 kPa incl. organ. ≤ 2%
Cohesive unsaturated	$t_{s;ult} = 25 \cdot \left(\frac{\Delta p_s}{p_{ref}}\right)^{0.17}$	No data (A formula for cohesive saturated can be used)	Δp_s = 100÷600 kPa Δp_b = 100 1000 kPa incl. organ. ≤ 2%
Comments: 1) values of Δp_s and Δp_b should be given in kPa 2) reference stress should be taken as p_{ref} = 1 kPa			

As in Figure 6, the $q_{b;ult}/\Delta p_b$ correlation in Figure 8d results from a very small amount of research data and will therefore need to be verified with further research tests.

Empirical formulas were created from the above correlations to calculate the ultimate unit resistances $t_{s;ult}$ and $q_{b;ult}$ of the soil. These formulas, which are listed in Tab. 2, can be used for engineering purposes to calculate the pile load capacity in accordance with EC7 recommendations [11].

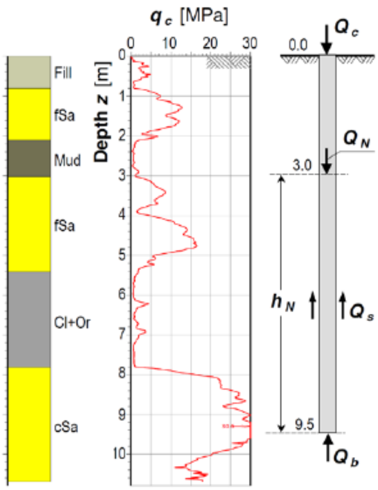
The load capacity calculation of SDP and DPDT screw displacement piles is based on the standard EC7 formula [11]:

$$R_{c;cal} = R_{s;cal} + R_{b;cal} = \sum_i A_{s;i} \cdot t_{s;ult,i} + A_b \cdot q_{b;ult} \quad (1)$$

where:

$A_{s;i}$, A_b, –pile shaft area in the "i" section and pile base area respectively

$q_{b;ult}$, $t_{s;ult,i}$ – ultimate unit soil resistances under the base and along the pile shaft, determined from the



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	230,0	51,0	281,0	0,34	0,84
1,0	279,2	72,1	351,3	0,44	1,44
2,0	339,0	102,0	441,0	0,56	2,56
3,0	379,8	124,9	504,7	0,65	3,65
4,0	411,7	144,2	555,9	0,72	4,72
5,0	438,2	161,2	599,4	0,79	5,79
7,0	481,5	190,8	672,2	0,89	7,89
9,0	516,6	216,3	732,9	0,98	9,98
12,0	559,9	249,8	809,7	1,10	13,10
15,0	596,0	279,2	875,3	1,19	16,19
20,0	596,0	322,4	918,5	1,28	21,28
25,0	596,0	360,5	956,5	1,36	26,36
30,0	596,0	394,9	990,9	1,43	31,43
35,0	596,0	426,5	1022,6	1,50	36,50
40,0	596,0	456,0	1052,0	1,56	41,56

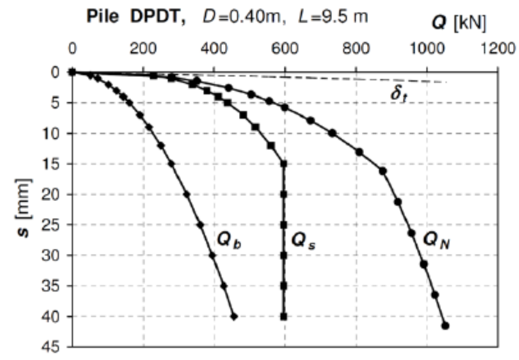


Figure 9.
An example of calculating and determining the *Q-s* characteristic of a DPDT pile

formulas in Table 1 or Table 2.

Areas A_b and A_s should be calculated assuming the nominal diameter D of the pile-forming auger.

3.3. *Q-s* characteristics of screw displacement piles

From the results of field pile load tests, generalized formulas of *t-z* and *q-z* transfer functions were derived for calculating the *Q-s* characteristics of piles according to the proposal of Gwizdała [12]. The discussed power functions are presented below:

$$t_s(s_s) = t_{s;ult} \cdot \left(\frac{s_s}{z_{s;f}}\right)^{0.28} \leq t_{s;ult} \quad \text{[kPa]}, \quad z_{s;f} = 15\ \text{mm} \tag{2}$$

$$q_b(s_b) = q_{b;ult} \cdot \left(\frac{s_b}{z_{b;f}}\right)^{0.50} \leq q_{b;ult} \quad \text{[kPa]}, \quad z_{b;f} = 0{,}1D \tag{3}$$

The resistance values of $t_{s;ult}$ and $q_{b;ult}$ in the above formulas are obtained from calculation procedures presented in sections 3.1 or 3.2. The values of the exponents $\alpha = 0.28$ and $\beta = 0.50$ were determined from statistical analyses, based on which it was established that they can be averaged and standardized for SDP and DPDT piles and for all soils. As a consequence, the transfer functions (2) and (3) can also be adapted to total pile resistances:

$$Q_s(s_s) = Q_{s;ult} \cdot \left(\frac{s_s}{z_{s;f}}\right)^{0.28} \leq Q_{s;ult} \quad \text{[kPa]}, \quad z_{s;f} = 15\ \text{mm} \tag{4}$$

$$Q_b(s_b) = Q_{b;ult} \cdot \left(\frac{s_b}{z_{b;f}}\right)^{0.50} \leq Q_{b;ult} \quad \text{[kPa]}, \quad z_{b;f} = 0.1D \tag{5}$$

In the presented method, the predicted pile settlement curve $Q_N(s)$ in load-bearing soils is obtained. It is a sum of the shaft resistance $Q_s(s)$ and the base resistance $Q_b(s)$ (Fig. 9).

In engineering calculations, shortening of the pile shaft, of axial stiffness EA, can also be taken into account in a simplified way according to the formula:

$$\delta_t(s) = \frac{Q_N(s) + Q_b(s)}{2 \cdot EA} \cdot h_N \tag{6}$$

where: h_N –pile length in bearing soil layers (Fig. 9).

3.4. Correlations between the CPT sounding and the screwing resistance of DPDT and SDP pile augers

Finding correlations between the results of in situ subsoil tests and SDP, DPDT and DPDT-S screwing pile auger resistances was one of the most important project tasks, as it is an important technological issue. A certain proposal regarding the prediction of screwing resistance for the SDP auger in cohesionless soils based on the CPT cone resistance q_c has already been presented in [9] and [13]. The value of their predicted M_T torque was divided into components M_{Ts} and M_{Tb} and made dependent on several additional factors, such as the distance between helixes on the auger, the speed of auger penetration, the vertical force of pressure and the current value of the auger embedment in the bearing layer. Unfortunately, the

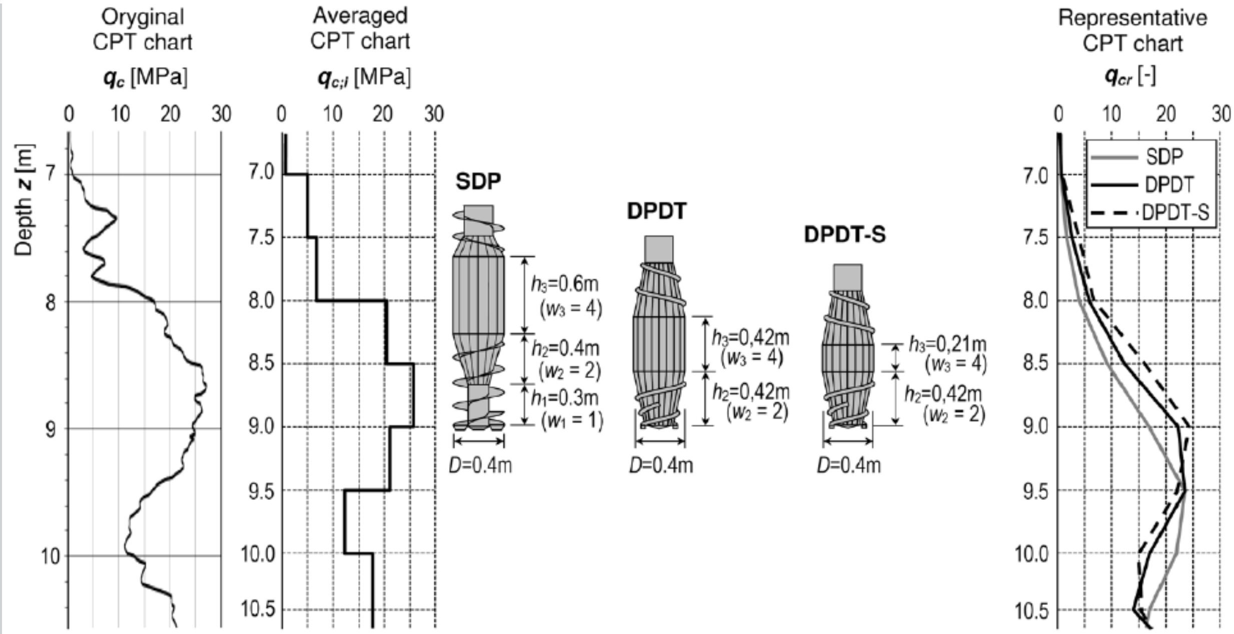


Figure 10.
Scheme for determining representative cone resistance values q_{cr} from CPT probing graph and for individual pile auger types

proposal turned out to be too complicated for engineering and practical purposes.

Instead, connections were sought between the torque M_T values generated during auger peneration and the only q_c resistance of a CPT(U) cone. Other parameters of the auger screwing process, such as unit auger rotations number n_R or the vertical pressure force Q_{Tv} were omitted, whilst recognising that these values are related to the value of torque M_T.

A direct comparison of the torque M_T value with the cone resistance q_c values at the same depths would be inappropriate. Therefore, the resistance q_c had to be appropriately averaged and recalculated according to the diagram in Fig. 10 to obtain a substitute q_{cr} graph, hereinafter referred to as a graph of dimensionless representative cone resistance. The q_{cr} value is referenced to the same depth as the auger tip, but represents the q_c resistances collected over the entire length of the auger. According to the diagram in Fig. 10, augers should be divided along their length into 2 or 3 sections with h_i lengths, to which appropriate w_i weights were assigned, determining the impact of individual sections on generating the resistance torque M_T.

In the conversion procedure, the actual q_c graph should first be replaced by a step graph with $q_{c;j}$ values averaged over 0.5 m or 0.25 m segments. Then, the representative resistance values $q_{cr;j}$ should be calculated at subsequent depths every 0.5 m or 0.25 m according to the formula:

$$q_{c;r;j} = \frac{\sum_i w_i \cdot q_{c;j;i} \cdot h_i}{1MPa \cdot \sum_i w_i \cdot h_i} \tag{7}$$

where:

$q_{c;i;j}$ – averaged cone resistance value q_c over the h_i length of the auger segment at z_j auger penetration depth.

The torque values M_T measured in the tests were linked (combined) with calculated representative cone resistances q_{cr}, determining the correlations shown in Fig. 11. The results come only from measurements on the test piles at experimental plots, as CPT probing was carried out only in these pile

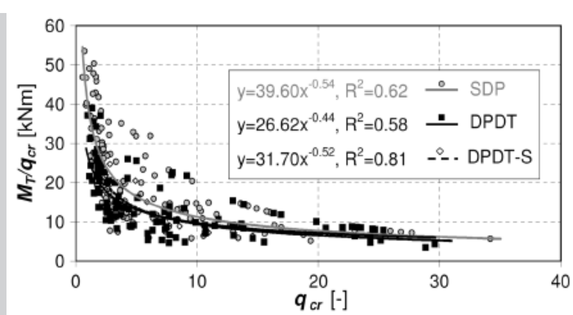


Figure 11.
Comparison of M_T/q_{cr} trend lines for all three augers from all experimental field plots

locations. The correlation points presented in Fig. 11 show individual trend lines for SDP, DPDT and DPDT-S augers.

Formulas were created from the trend functions presented in Fig. 11 to calculate the torque M_T values based on representative, dimensionless cone resistance values q_{cr}. Due to the visible significant point dispersion in the graph, the formulas were multiplied for safety by a correction factor of 1.25.

The final versions of the derived formulas are shown below:

– for SDP auger: $$M_T = 49.5 \cdot (q_{cr})^{0.46} \quad (8)$$

– for DPDT auger: $$M_T = 33.28 \cdot (q_{cr})^{0.56} \quad (9)$$

– for DPDT-S auger: $$M_T = 39.63 \cdot (q_{cr})^{0.48} \quad (10)$$

The above formulas are shown in graph forms in Fig. 12. Ultimate resistance values q_{cr} for individual augers and for a pile drilling rig with a maximum torque $M_{T;ult}$ = 200 kNm were also marked.

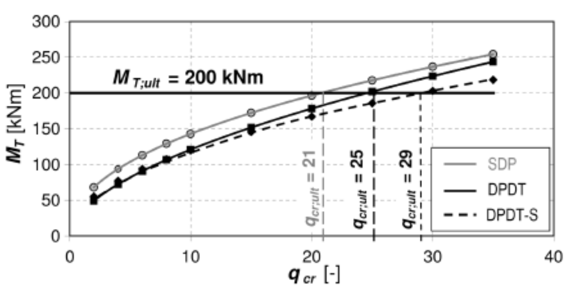


Figure 12.
Derived M_T dependencies on $q_{c;r}$ for the tested SDP, DPDT and DPDT-S pile augers

After performing calculations and preparing the $q_{c;r;j}$ and $M_{T;j}$ diagrams based on the actual (original) cone resistance q_c from CPT sounding, one can approximately determine whether and to what depth it will be possible to install a displacement pile in a given place, using the given auger type and given pilling rig.

4. CONCLUSIONS

The results of the "DPDT-Auger" research project should be assessed positively, and therefore the project should be considered justified. The field research tests and analyses allow for the formulation of several conclusions, the most notable of which are as follows:

1) The prototype, proprietary DPDT and DPDT-S pile augers generate lower torque values M_T than a standard SDP auger during penetration. However, the torque decrease takes place at the cost of an increased rotations number n_R and an extended time of pile driving t_D. The overall balance of screwing resistance should be considered favourable for the DPDT and DPDT-S augers, as the generation of a lower torque value allows for greater drilling depths and longer pile lengths, as well as for more successful crossing over stronger soil layers.

2) Piles made with SDP and DPDT (DPDT-S) augers have very similar interaction characteristics with various subsoil types. Statistically, the bearing capacity and stiffness of both pile types are comparable.

3) The research and results analyses carried out for the project enabled the detection and numerical definition of various correlations between the in situ subsoil tests and the results of the auger and pile tests. The derived correlations allowed the development of empirical computational and prognostic methods that can be used in the design and execution of screw displacement piles in practice. They have already been implemented by project consortium member, Budokop Geotechnika.

The correlations and calculation methods presented in this article refer to piles made with the D = 0.40 m shaped augers shown in Fig. 2. The proposed formulas may also be used in the case of other auger diameters, but only after appropriate recalculations (adjustments).

The presented calculation methods are relatively recent, preliminary versions. They are still in the development phase and in the future will certainly be subject to verification, correction or modification in accordance with subsequent research.

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