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THE ANALYSIS OF SOIL RESISTANCE DURING SCREW DISPLACEMENT PILE INSTALLATION

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Abstract: The application of screw displacement piles (SDP) is still increasing due to their high efficiency and many advantages. However, one technological problem is a serious disadvantage of those piles. It relates to the generation of very high soil resistance during screw auger penetration, especially when piles are installed in non-cohesive soils. In many situations this problem causes difficulties in creating piles of designed length and diameter. It is necessary to find a proper method for prediction of soil resistance during screw pile installation. The analysis of screw resistances based on model and field tests is presented in the paper. The investigations were carried out as part of research project, financed by the Polish Ministry of Science and Higher Education. As a result of tests and analyses the empirical method for prediction of rotation resistance (torque) during screw auger penetration in non-cohesive subsoil based on CPT is proposed.

Key words: *screw displacement pile, pile installation, pile auger, torque, soil resistance*

1. INTRODUCTION

During the installation of SDP pile, when the auger penetrates the non-cohesive subsoil, high soil resistance is observed. This screw resistance is one of the biggest problems of SDP pile technology and is a subject of ongoing scientific investigations and analyses. It was also the reason that many types of screw auger have already been introduced into practice. It is believed that soil resistance could be reduced by appropriate auger construction. Due to the difficulties connected with the installation of screw displacement piles in various types of soil conditions, these piles are often omitted in geotechnical projects.

High soil resistance during screw auger penetration means the high value of torque (M_T), which should be applied to rotate the auger. Therefore, very massive drilling machines with high torque (at least 200 kNm) need to be used for screw displacement pile installation. The analysis of installation effort connected with SDP piles was carried out, among others, by NeSmith [10].

The problem is additionally complicated due to the fact that high soil resistances during the installation not always mean the high bearing capacity of screw pile. The analogy to driven piles, where the high blowing resistances indicate the high pile bearing capacity, cannot be taken in the case of SDP piles. This results from the fact that the load bearing capacity of screw displacement piles is primarily based on the shaft resistance Q_s, [4–6].

Learning from practice shows that we rather will not be able to reduce significantly the soil resistances by changing the shape or the construction of screw auger. The only way to solve the problem seems to identify the phenomena occurring in the soil during the screwing process and to propose a method for predicting the soil resistances.

This paper presents the results of the author's own model and field tests as well as theoretical analyses concerning soil resistances during screw auger penetration in non-cohesive soil. Model and field tests were correlated with CPT tests. Thanks to these results, the empirical method of screw torque M_T value prediction based on CPT tests has been developed and presented.

2. DESCRIPTION OF SCREW AUGER PENETRATION PROCESS

The main task of screw pile auger is to create a hole in the ground by radial soil displacement and to fill the hole with the concrete. Bottom part of the auger is helical but in the upper part the diameter of auger core gradually increases. Thanks to its shape the auger penetrates the soil during rotation and displaces the soil radially. Sometimes, a vertical compressive force is added from drilling machine to initiate the auger penetration. In other cases a tension force is used to decrease the penetration velocity and to reduce the torque value.

Screwing process initiates a significant increase of radial stresses in the surrounding soil. These stresses are the main reason of high soil friction around the auger surface. There are also soil resistances under the auger base.

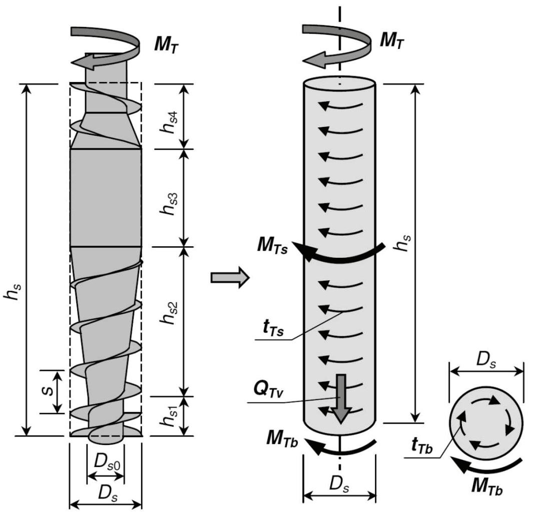

Fig. 1. Simplified scheme of SDP auger taken for analysis

The insertion of a drilling tool into the ground is a complex process, difficult to theoretical describe. Therefore, a simplified scheme of the auger was taken for analysis. In this scheme, presented in Fig. 1, the real auger is represented by the equivalent cylinder.

It is assumed that the total value of torque M_T consists of two components: M_{Ts} and M_{Tb}

$$M_T = M_{Ts} + M_{Tb} \,. \tag{1}$$

M_{Ts} is connected with soil friction t_{Ts} around the auger shaft and is generated by the auger rotation. M_{Tb} is connected with soil unit friction t_{Tb} under the auger base and is generated by the rotation and auger vertical movement. Components M_{Ts} and M_{Tb} are defined by the formulas

$$M_{Ts} = \frac{\pi \cdot D_s^2}{2} \cdot \sum t_{Ts;i} \cdot h_{s;i} \,, \tag{2}$$

$$M_{Tb} = \frac{\pi \cdot D_s^3}{12} \cdot t_{Tb} \,. \tag{3}$$

Screw resistance is also defined by the number of auger rotations n_T per unit depth of penetration. In the author's opinion M_T and n_T are the most important parameters of SDP pile installation. In practice, in the reports of screw displacement pile installation there is given the information about: oil pressure in the hydraulic rotary tool, rotation velocity RPM (rotation per minute) and penetration velocity (meters per hour). M_T and n_T values are obtained from recalculating the

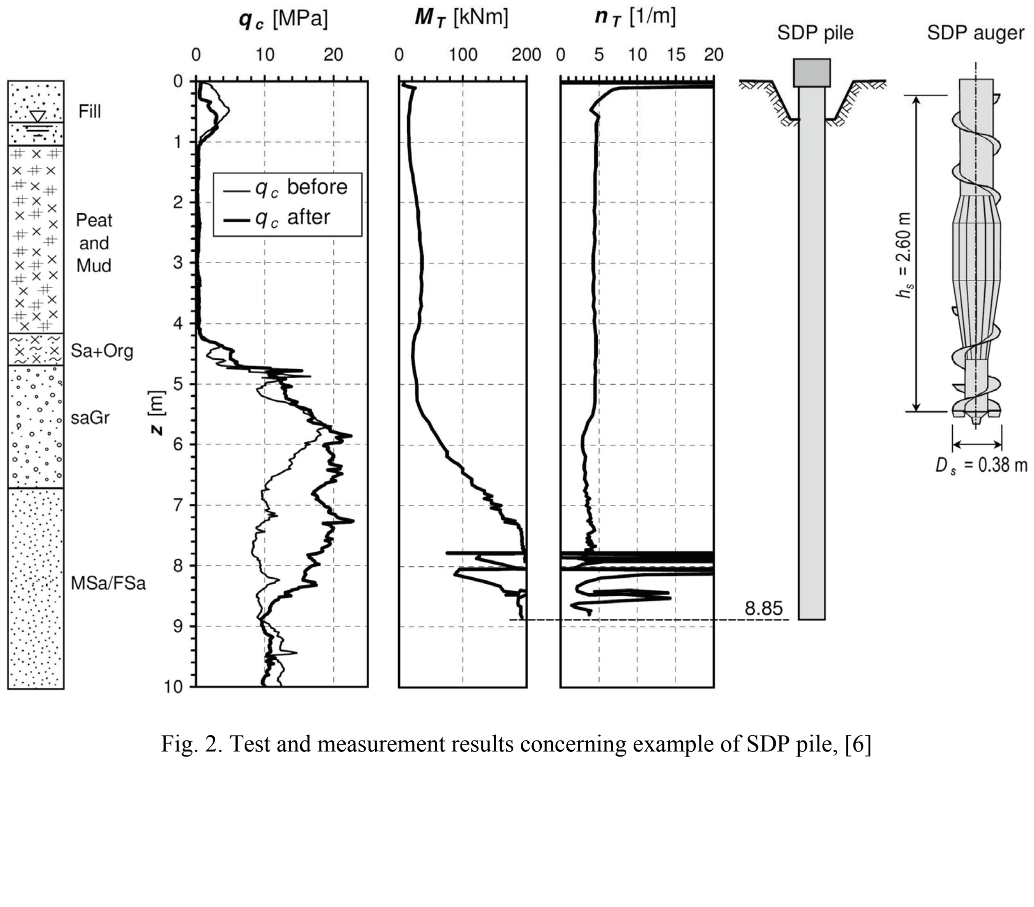

Fig. 2. Test and measurement results concerning example of SDP pile, [6]

three parameters mentioned. In most drilling machines, the value of torque M_T depends on hydraulic oil pressure and on RPM (the smaller the RPM, the higher the M_T for a given oil pressure).

Figure 2 presents the example of measurement results concerning SDP pile installation in correlation with CPT test of subsoil. CPT was carried out before and after pile installation. The pile was installed by drilling machine of maximal torque M_T = 200 kNm and by the auger of shape presented in the figure.

In the CPT diagram one may note that after pile installation there is an increase of q_c resistances in the region around the pile shaft, but under the pile base that increase is not very high. Similar phenomenon was observed with regard to the other SDP piles tested. This allowed us to conclude that screw displacement piles affect the soil conditions (density and stress level) mainly around their shafts.

In the M_T and n_T diagrams one may notice that during auger penetration into the bearing stratum an intensive increase of torque is observed with constant value of the rotation number n_T (about 4 rotations per meter). When the torque reached the maximal value of 200 kNm, at the depth of 7.5 m under the ground level, the penetration velocity was reduced. As a result, the n_T value increased whereas the M_T value decreased. Thanks to such actions it was possible to create a pile of length L = 8.85 m. This example shows that the torque value can be influenced by regulation of auger penetration velocity, thus by rotation number n_T.

3. MODEL TESTS

Model tests were conducted using SDP auger models prepared in 1:7.5 scale in two diameters (Fig. 3). Auger model SDP1 represents the original auger of 400 mm in diameter, while model SDP2 represents the original auger of 500 mm in diameter. The experiments were carried out at the Geotechnical Laboratory in Gdańsk University of Technology. The research device consists of steel container (2.0 m diameter and 2.0 m high) for soil. Moist fine sand was prepared with appropriate density achieved by vibration and controlled by CPT tests.

The augers were screwed into the soil using hand operated device and vertical load of constant value of 0.5 kN. Soil resistances during screwing were measured in terms of torque M_T and number of rotations n_T per each 0.1 m of auger penetration. Several series of tests were carried out. Apart from the measurements of soil resistances during auger penetration also the SDP and "Atlas" pile models were installed and tested in respect of their bearing capacity. A detailed description of pile model tests is presented also in other author's work [3].

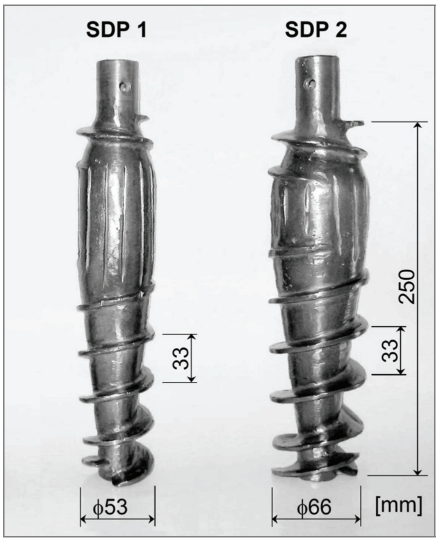

Fig. 3. Models of SDP augers (model scale 1:7.5)

During screw auger penetration usually only the total value of torque M_T is measured, and it is difficult to divide its value into M_{Ts} and M_{Tb} components. Therefore, in one of the tests the measuring of screwing resistances was performed in a special way. It was assumed that if the auger vertical penetration was blocked, then during rotation only the M_{Ts} component was measured. Before blocking the total M_T value was measured. M_{Tb} component was then calculated as a difference between M_T and M_{Ts}. During the test, which is shown in Fig. 4, also the value of vertical force Q_{Tv} was measured. The author named this tension force as "auger thrust". The measurements of M_T, M_{Ts} and Q_{Tv} were carried out every 0.1 m of penetration from 0.5 m to 1.0 m of depth.

The results of measurements, which were done for both augers SDP1 and SDP2, are presented as the diagrams in Fig. 5, together with diagrams of cone resistances q_c and rotation numbers n_T.

Next, using the auger scheme presented in Fig. 1, the values of unit soil resistances t_{Ts} and t_{Tb} were calculated and presented in Fig. 6 as diagrams together with diagrams of ratios t_{Ts}/q_{cs} and t_{Tb}/q_{cb}. The q_{cs} value was taken as an average q_c from the auger length h_s, whereas q_{cb} was taken as an average q_c of $–D_s$ to $+D_s$ region around the auger base level.

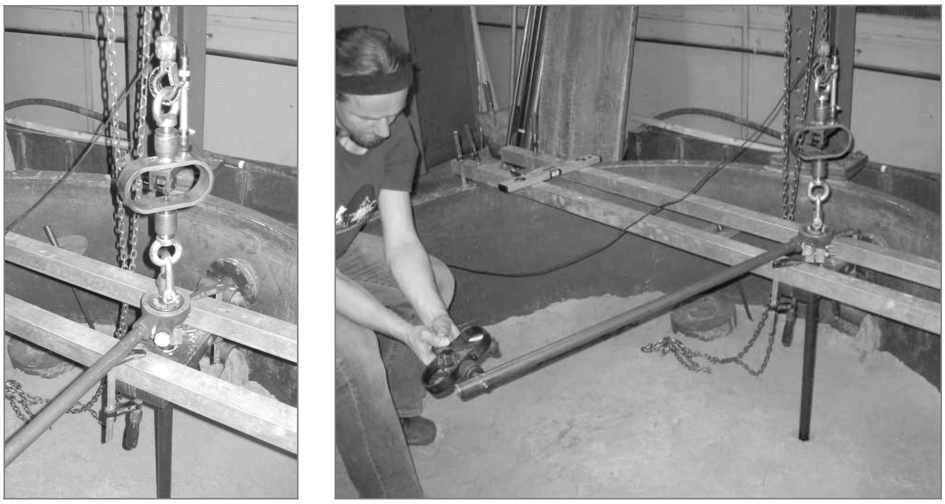

Fig. 4. Measurement of torque component M_{Ts} and auger thrust Q_{Tv} in model test

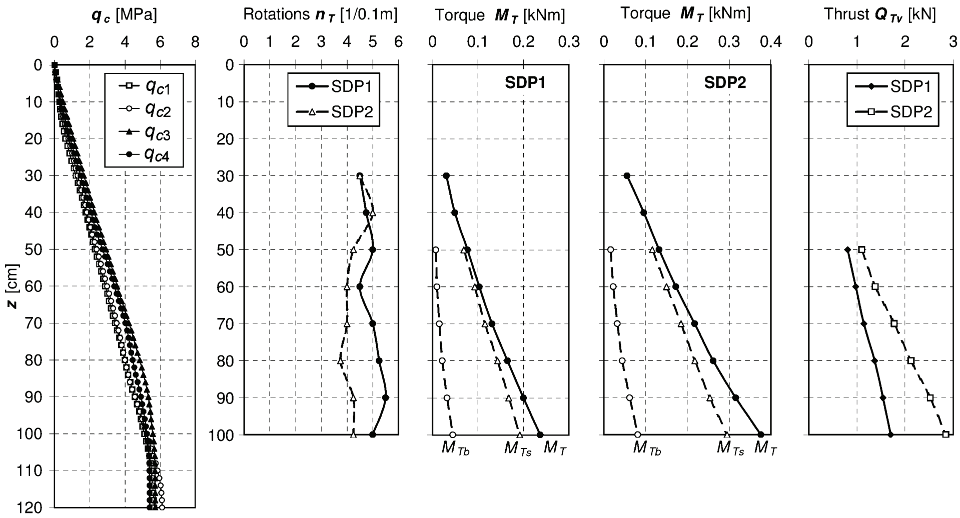

Fig. 5. The results of auger SDP screwing tests with measurements of torques M_T, M_{Ts}, M_{Tb} and force Q_{Tv}

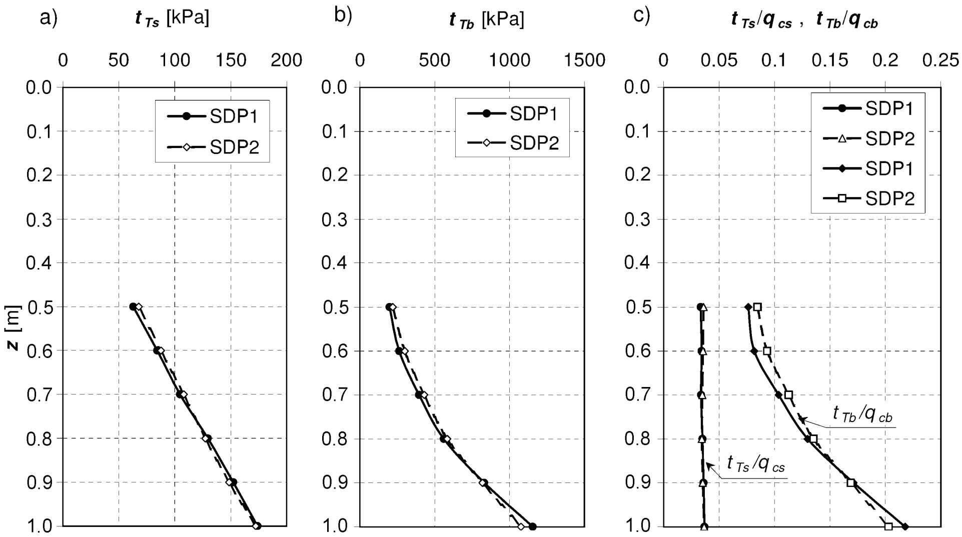

Fig. 6. Unit friction resistances t_{Ts} and t_{Tb} and their relations to cone resistances q_c

It can be noted that ratio t_{Ts}/q_{cs} is constant along the whole depth, which means that unit resistance t_{Ts} is proportional to cone resistance q_c. On this basis the following relation is created

$$t_{Ts} = 0.035 \cdot q_{cs} \,. \tag{4}$$

The ratio t_{Tb}/q_{cb} is not constant but is increasing with depth. It was assumed that this increase is caused by auger thrust Q_{Tv}. The mechanism of auger thrust initiation can be explained by analogy to ordinary screw. In such a screw, when the friction on the thread is neglected, a relation between M_{Ts} component of torque and thrust Q_{Tv} results from the principle of energy conservation. In the case of auger which is penetrated into the soil the following relation is assumed

$$Q_{Tv} = a \cdot \frac{2\pi \cdot M_{Ts}}{n_T \cdot s} \tag{5}$$

where

s – pitch of the auger helix,

a – reduction factor, taking into account the losses caused by the soil friction and by the fact that vertical velocity of auger insertion is less than it would result from pitch of helix s ($a < 1.0$, the exact value of a is not known).

The number of auger rotation per 1.0 m (n_T) should be taken into account as a value without units.

The thrust Q_{Tv} causes the auger base impact on the soil by vertical pressure q_{Tb} which can be expressed by the formula

$$q_{Tb} = \frac{4Q_{Tv}}{\pi D_s^2} = 8a \cdot \frac{M_{Ts}}{n_T \cdot s \cdot D_s^2} \,. \tag{6}$$

The vertical pressure q_{Tb} influences directly the soil friction t_{Tb} under the auger base. The following relation is assumed

$$t_{Tb} = q_{Tb} \cdot \mu_{Tb} \tag{7}$$

where μ_{Tb} – friction coefficient of the soil under the auger base.

On the basis of model test results it was concluded that the value μ_{Tb} is not constant but increases with depth approximately proportionally to the increase of cone resistance q_c. The following relation is assumed

$$\mu_{Tb} = b \cdot \frac{q_{cb}}{p_{\text{ref}}} \,, \tag{8}$$

where

$p_{\text{ref}} = 1.0$ MPa – reference stress,

b – conversion factor (not known).

Equation (7) takes the form

$$t_{Tb} = 8a \cdot \frac{M_{Ts}}{n_T \cdot s \cdot D_s^2} \cdot b \cdot \frac{q_{cb}}{p_{ref}} \,. \tag{9}$$

After introducing two new coefficients

$$m_{Ts} = \frac{M_{Ts}}{s \cdot D_s^2 \cdot p_{\text{ref}}} \tag{10}$$

and

$$m_{Tb} = 8 \cdot a \cdot b \tag{11}$$

we receive a new form of equation (9)

$$t_{Tb} = \frac{1}{n_T} \cdot m_{Ts} \cdot m_{Tb} \cdot q_{cb} \,. \tag{12}$$

The coefficient m_{Tb} was determined experimentally from test results by using back analysis method. It was not necessary to determine values of a and b coefficients separately. The m_{Tb} value was found to be about 4.40 and was approximately constant in relation to depth and similar in the case of both augers SDP1 and SDP2.

Finally, from the analysis one can obtain empirical equations for the calculation of torque components M_{Ts} and M_{Tb} and total torque M_T of screw displacement augers on the basis of cone resistances q_c. Moreover, the analysis has shown that M_{Ts} component depends mainly on the cone resistance q_c, whereas M_{Tb} component depends on M_{Ts} value, cone resistance and number of auger rotations per unit depth n_T.

4. FIELD TESTS

A method for prediction of soil resistance during screw auger penetration was prepared also for piles in natural scale. This method concerns SDP and CMC (Controlled Modulus Column) augers. There were applied the same assumptions and very similar equations as in the model test analyses, but several additional factors and effects had to be taken into account. These factors concerned the auger shape, non-homogeneity of soil profile and stress level in the subsoil.

The same scheme of auger as presented in Fig. 1 and the same equations (1)–(3) of M_T, M_{Ts} and M_{Tb} calculations were applied.

After many trial replications of torque values measured in the field tests, the following formulas for t_{Ts} and t_{Tb} resistances were determined

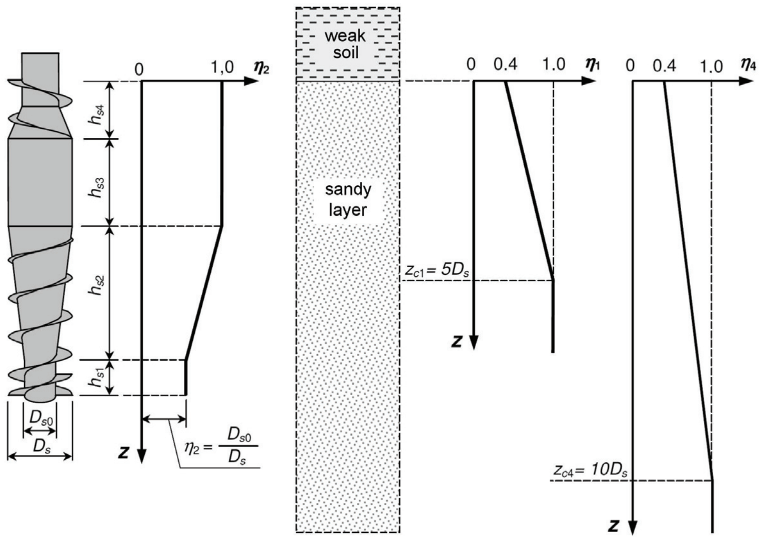

Fig. 7. Diagrams for determination of η_1, η_2 and η_4 coefficients

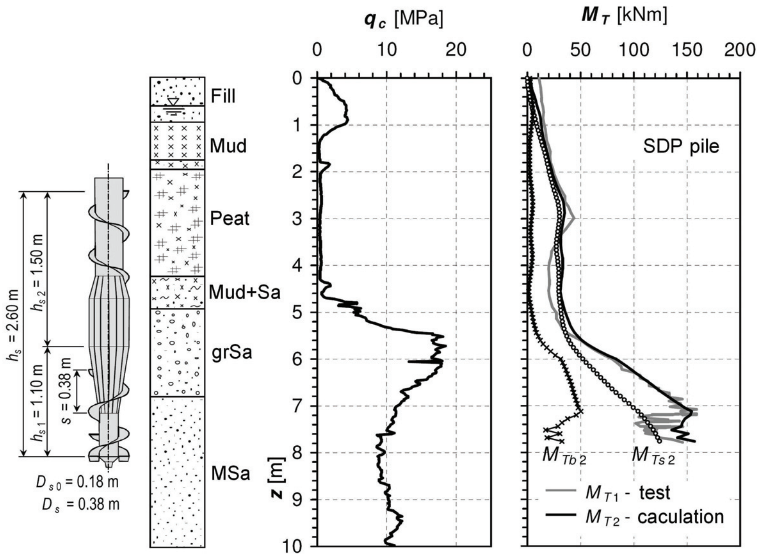

Fig. 8. Torque M_T prediction for the SDP pile installation on the field site

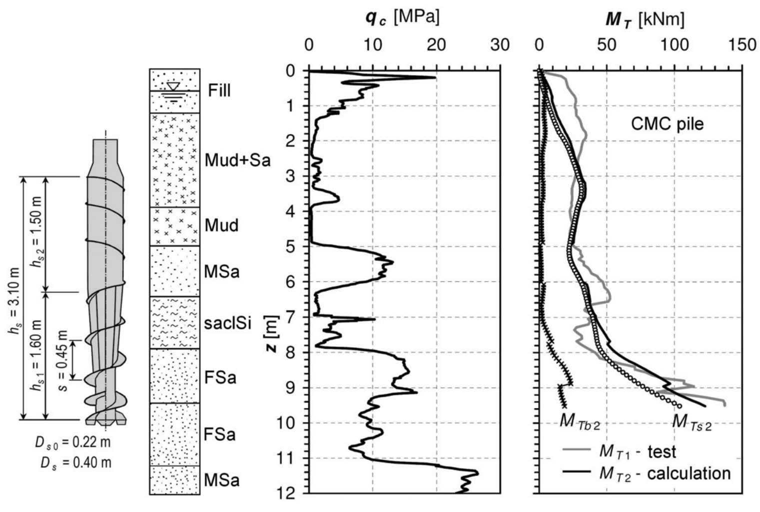

Fig. 9. Torque M_T prediction for the CMC pile installation on the field site

$$t_{Ts} = 0.035 \cdot \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot q_{cs} \quad \text{[kPa]}, \qquad (13)$$

$$t_{Tb} = 1.2 \cdot \eta_3 \cdot \eta_4 \cdot m_{Ts} \cdot \frac{q_{cb}}{n_T} \quad \text{[kPa]}, \qquad (14)$$

where

η_1, η_4 – coefficients dependent on the depth of auger penetration in bearing soil layer,

η_2 – coefficient of auger shape influence,

η_3 – coefficient of stress level in the subsoil.

Coefficients η_1, η_2 and η_4 are read from diagrams presented in Fig. 7, whereas η_3 coefficient is calculated from the formula

$$\eta_3 = \frac{\sigma'_{v0}}{100\ \text{kPa}} \qquad (15)$$

where σ'_{v0} is a vertical effective stress in the subsoil.

The value of m_{Ts} coefficient is calculated using formula (10).

The number of auger rotations per unit depth n_T which has to be applied in equation (14) is unknown and we must assume its value. It was mentioned earlier that the n_T value can be controlled during screwing process by the piling machine operator. In the calculation we should take the planned or maximal accepted value of n_T (usually no more than 20 to 40 rotations per meter).

4.1. COMPARISON OF PREDICTED AND MEASURED SCREW RESISTANCES

Figures 8 and 9 present the results of calculated replications of real screw resistances measured during the installation of two selected piles in the field. Particular emphasis was placed on M_T value prediction in the bottom part of subsoil when the auger was penetrated in the bearing sandy layer. The organic soils in the upper parts of subsoil were less important, then the screw resistances in these layers were taken approximately as: $t_{Ts} = f_s$ and $t_{Tb} = 5 \cdot f_s$, where f_s is the sleeve friction measured in CPT test. The values of η_1, η_2, η_3 and η_4 coefficients were taken as equal to 1.0 in organic soil. The values of n_T were taken as equal to those read from the pile installation reports.

On the basis of diagrams presented in Figs. 8 and 9 it can be concluded that the proposed method for prediction of soil resistance during SDP and CMC auger penetration in non-cohesive soils provides good results.

5. CONCLUSIONS

The tests and analyses presented in the paper showed that rotation resistances during screw displacement auger penetration in non-cohesive soils depend on soil strength properties (expressed by CPT cone resistances q_c), auger geometry and screw technique (the velocity of rotation and penetration). The total value of torque M_T generated by screwing process can be divided into two components: M_{Ts} – moment resulting from soil friction around the auger shaft and M_{Tb} – moment resulting from soil resistances under the auger base.

The calculation method developed as a result of tests and analyses allows us to predict the rotation resistances (a value of torque M_T) during SDP auger penetration into non-cohesive subsoil on the basis of CPT results. The method was verified positively with several practical examples of SDP and CMC pile installation in the field. On the base of it, we will be able to know what energy of piling machine is required to install the designed screw displacement pile. This prediction method can be applied to design screw displacement piles together with the author's own method for pile bearing capacity calculation [7] or with other calculation methods, proposed, for example, by Bustamante and Gianeselli [1], [2], Maertens and Huybrechts [8] or by NeSmith [9].

It should be underlined that many elements of the calculation method proposed were assumed in a simplified way. Due to this fact it may not work well in every case. This method should rather be considered as a preliminary proposal, which require many tests and verifications and will certainly be subjected to modifications.

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