Drilling Performance Prediction for Screwed Displacement Piles Based on CPT Testing

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ABSTRACT: The application of specially modified screw displacement piles (SDP) has many advantages such as high capacity per unit length, low spoil volume, and high production rate. On the other hand, production rate of SDP piles is highly dependent on the ground conditions. Penetration rate is slower in dense granular ground and in very stiff/hard cohesive layer. Semi-empirical analysis method is developed to consider drilling time of a pile at bid or design phase. Main formulas are based on theoretical considerations on drill resistance and drill rig operation. Empirical parameters are introduced to achieve a good fit with the filed experience. The database used to set and validate the semi-empirical method is based on drilling monitoring data. Approximately 4000 pile records from two major projects in Hungarian river deposits are considered.

Keywords: Screwsol, screw displacement pile; pile installation; drilling parameters; cone penetration test; pile layout optimization

1. Introduction

Application of piles as deep foundation is a wide spread practice in the industry. The aim of the piles to transfer the load from the foundation to a relatively competent load bearing layer. A wide range of pile system is available, and each system have unique features.

In this paper displacement piles are under consideration. General information on displacement piles are first summarized is Section 1. Specific design consideration applied to displacement piles, since installation depth is limited by the rig capabilities. Once drilling resistance exceeds a limit, drilling rate and production rate drop. Production rate has a high impact on cost of piling. Hence, successful pile design optimization relay on pile capacity and drilling time calculation too. These considerations are summarized in Section 2.

In Section 3, a drillability classification is introduced, where drilling resistance of the ground is classified to 3 classes. The classes are correlated with CPT testing result in Section 4. Classification can be used to optimize design and avoid pitfalls where deadline cannot be met due to low production rates.

In Section 5 and 6 a specific project example is presented, where the design was optimized in order to increase profit and risk of low production rat was avoided in order to ensure project is delivered on deadline.

1.1. Displacement piles

Displacement Screw Piles (DSP), also known as rotary displacement piles, are created in a similar method to CFA piles. Instead of a full-length hollow auger, a shorter displacement tool is followed by hollow stem drill rods to reach the required depth. As piles are bored, the specially designed hollow tool displaces the surrounding soil laterally, and consequently high torque and pull-down rigs are required. Having reached the required depth, concrete is pumped through the hollow drill string and introduced from the base of the bore whilst the tool and rods are extracted. Cages are inserted after the concreting process. Displacement piles combines the advantage of the driven piles in terms of load bearing and the flexibility of the bored piles.

The drilling parameters are highly affected by the specific type of pile and pile rig. Some results are general observation, but the exact resistance, drilling parameters and CPT results are applicable for Screwsol pile and Bauer BG 24 Rig.

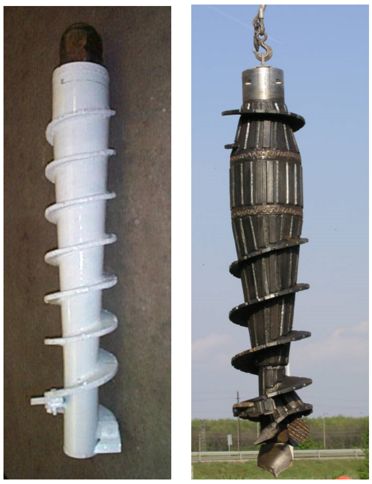

Figure 1. 330/500 and 530/700 diameter drill bits

Detailed information on application in fine grain soil and river deposits in Hungary presented in [1], [2].

1.2. Drilling parameters

Automated data acquisition systems are widely available for most drill rigs. Several parameters are measured, recorded and stored during drilling and concreting of the piles (see Figure 2).

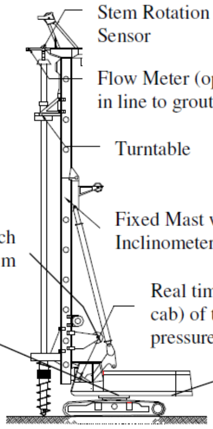

Figure 2. Data acquisition system [3]

Typical drilling parameters and the parameter calculated from them are the following:

- Grout pressure sensor: concrete pressure (bar)
- Stem rotation proximity sensor: drill bit rotation per minute (RPM)
- Mass inclinometers, stem inclination (deg)
- Torque fluid pressure sensor: Torque (kNm)
- Stem depth: Penetration rate per minute (m/min)

Drilling parameters are recorded and then post processed in an office or processed in real time on the rig. There are several applications of drilling parameters:

- Pile capacity was calculated from drilling parameters by several authors [4], [6]. This allows contractors to fit the pile length to the encountered ground conditions during execution phase, while ensures pile capacity is in accordance with design assumptions.
- Other application is to use ground investigation results to calculate required torque and to select required piling rig specifically for the site. A semi empirical method is presented by [5].
- Drilling parameters are powerful quality control tools. Drill logs can be prepared and submitted to the client. It serves as a proof of pile quality [3] by indicating pile drilling parameters or simply pile length, diameter, inclination, concrete consumption.
- Drilling parameters are used for research purposes. Experience gained on site in combination with ground exploration results and with numerical modelling is a powerful tool to have a better understanding of drilling processes [7].

It must be noted, that the automated data acquisition systems are not standardized and certified measuring tools. Therefore, their outputs must be handled with caution. Calibration, regular maintenance is needed carried out by a mechanical engineer.

1.3. Aim of the paper

Several feasible of combinations of pile number and length can be selected during the design process of pile foundations. For example, load-bearing capacity of 4 pcs of 10m long piles below a pile cap may be equal to 5 pcs of 8m long piles. The costs of the two equivalent solutions depend on the material costs (proportional with the pile length) and time dependent costs (proportional with drilling time). Hence, there is a need to understand and predict drilling rate to design economical pile foundations. The key elements in a successful pile design optimization are the following:

- understand ground condition including spatial variability
- have a reliable pile capacity calculation
- have reliable estimate of production rate

Present paper focuses on the 3rd point above, the proper estimation of the drilling time. Based on the drilling time the production rate can be estimated by the contractor. This estimate allows us to consider material related costs and time-related costs also.

2. Pile Design

Displacement pile has advantages over drilled pile. The displaced ground causes compaction in the surrounding soil and therefore increases pile capacity [5]. In addition, the extracted soil is minimal.

The authors found that displacement piles are a good option in typical Hungarian river deposits. It typically consists of soft silty clay layers and dense sand or gravels. Under these conditions pile toe level is recommended to be selected where the first load bearing dense sand or gravel layer is. The shaft resistance usually less than 50% of the piles.

The pile resistance can be reliably determined by CPT-based calculation calibrated on past static load test results [8]. Results of this paper are based on the calculation presented in [9].

In practice, the focus is on an optimized pile design. Displacement and driven pile design optimization have a specific consideration. Pile capacity and installation effort are proportional to each other [4]. At the same time both pile capacity and installation effort are highly nonlinear with depth. For example, often by increasing the pile length from 9 to 10 meters both the installation effort and pile capacity doubles. Material related cost per unit pile capacity typically lower when depth increase and time-related cost per unit pile capacity increases by longer piles. Thus, pile optimization is a balancing act, where the time and material related costs are balanced.

This unique design consideration creates the need to estimate production rate and drilling time for displacement pile.

3. *Ground Drillability*

An experience-based classification system is being set up, in order to improve accuracy of the production rate prediction. Three drillability classes were defined. The findings presented here are applicable for granular river deposits, Bauer BG25 rig with Screwsol 43/60 pile diameter. The 3 drillability class is not a ground property but the combination of rig properties, drilling tool geometry and ground properties. It indicates the required time and effort to drill displacement pile in a given depth. Drilling parameters gathered on site are considered to classify the drillability.

3.1. *Drilling parameters gathered on site*

As it is explained in Section 1.2, several drilling parameters are measured and recorded during pile installation. The parameters of the borehole and machine are collected in real-time via the B-TRONIC electronic monitoring and control system. Those data are then extracted with B-Report.

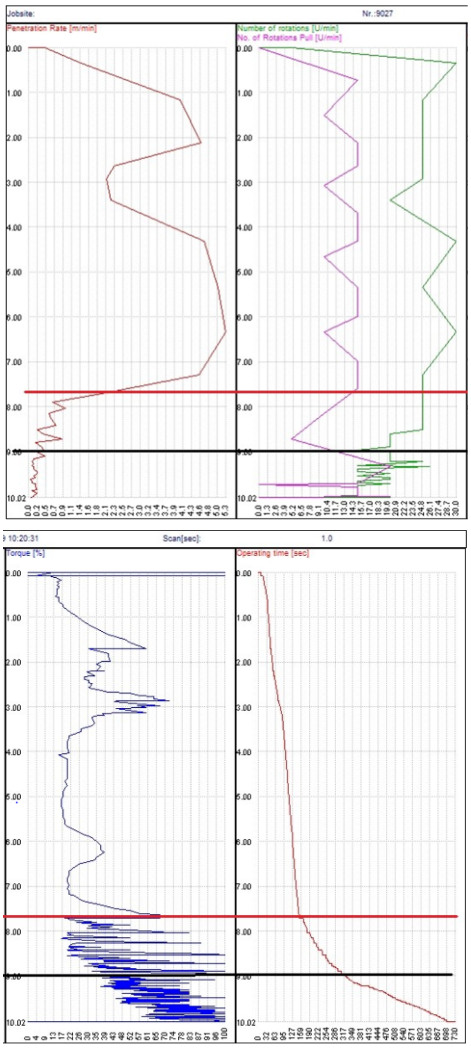

Figure 3. Data recorded during drilling: (Left to right) Penetration rate (m/min), Nr of rotation during drilling and concreting (RPM), Torque (%) and drilling time (s). Drillability classes: Good above red line, fair above black line, poor below black line.

The data is then post-processed using a tailor-made Python code. Post-processing steps are the following:

- Read individual data file for each pile
- Separate the data measured during drilling and concreting.
- Combine all data into one excel file.
- It then can be used for calculation or visualization. For calculations Excel, for visualization Voxler was used.

As it can be seen in Figure 3, there are 3 distinct classes of drilling time and effort:

- Good: Penetration rate is typically between 3-7 m/min. The drilling requires low working pressure and torque. The number of rotations per minute is around the maximum (30 U/min). (above black line)
- Fair: Penetration rate dropped to app.1m/min. Working pressure reaches maximum (~280bar) and is fluctuating. Torque is fluctuating as well but rarely reach 100%. Number of rotations per minutes start decreasing but does not fall drastically. (between black line and red line)
- Poor: The working pressure reaches a maximum, while the number of rotations is at its lowest (15-25RPM). The percentage of torque used is high, and the penetration rate is around 0.1m/min. (below red line).

Good drillability indicates soft ground. Fair drillability indicates that the ground is competent, and the load bearing ground is reached. Poor drillability indicate the rotation of the drill bit slows down since the ground difficult to penetrate.

3.2. *Statistical analysis of the data*

The drilling parameters were analyzed for several drilling and by one. The 3 drilling class were identified, and the range of typical drilling parameters corresponds to the drillability classes are gathered to a spreadsheet. Penetration rate, number of rotations, torque, working pressure were considered. In Figure 4 the penetration rate of the 3 classes are shown.

drilling	Drilling time (sec)			Total drilling time	Time in poor layer (%)	Thickness of the Layer			Total drilling depth	Thickness of poor layer (%)	Average penetration rate		
	good	fair	poor			good	fair	poor			good	fair	poor
9007	141	70	176	387	45%	8,0	0,9	0,6	9,5	7%	3,40	0,77	0,21
9019	145	117	378	640	59%	7,6	1,3	1,1	10,0	11%	3,14	0,67	0,18
9021	92	132	235	459	51%	5,9	2,9	1,2	10,0	12%	3,85	1,32	0,32
9027	159	158	381	698	55%	7,7	1,3	1,0	10,0	10%	2,91	0,49	0,16
9029	193	83	277	553	50%	7,6	1,3	1,2	10,0	12%	2,36	0,90	0,26
9035	130	105	211	446	47%	7,1	1,5	0,9	9,5	10%	3,28	0,86	0,26
9041	115	55	204	374	55%	6,9	1,1	1,6	9,5	17%	3,60	1,15	0,46
9049	136	649	210	995	21%	5,5	2,9	1,0	9,4	11%	2,43	0,27	0,29
9056	125	144	471	740	64%	6,2	1,7	1,6	9,5	17%	2,98	0,71	0,21
9058	150	117	386	653	59%	6,1	1,9	2,6	9,6	27%	2,44	0,97	0,40
9067	90	317	323	730	44%	5,8	2,4	1,4	9,5	14%	3,87	0,44	0,25
9084	155	225	252	632	40%	7,0	1,5	1,1	9,6	12%	2,71	0,40	0,26
9031	240	205	371	816	45%	7,7	1,2	1,2	10,0	12%	1,93	0,34	0,19
9103	153	112	865	1130	77%	6,0	1,4	2,2	9,5	23%	2,35	0,72	0,15
9171	117	156	567	840	68%	6,5	1,2	1,9	9,6	20%	3,33	0,46	0,20
9175	82	158	370	528	70%	6,6	1,5	1,5	9,6	16%	4,83	0,57	0,24
9178	108	42	259	409	63%	6,0	1,6	2,1	10,6	20%	3,31	2,21	0,49
9182	120	91	279	490	57%	7,1	1,2	1,4	9,6	14%	3,55	0,76	0,29
Averages	136	163	345	640	54%	6,7	1,6	1,4	9,7	15%	3,13	0,78	0,27

Figure 4. Penetration rate for drillability classes

After gathering a good amount of data, a statistical analysis was carried out. Drillability class for 13 pile (Figure 4) was determined. The penetration rate for all 3 classes was considered. The average penetration rate for "good" is 3,13; "fair" is 0,78; "poor" is 0,27. In order to determine boundary between the classes, the empirical distribution of the penetration rate was considered. The empirical distribution function of the penetration rate for 3 drillability classes shown in Figure 5. Limits are then set up between the three class. Only 18% of the sections classifies as "poor" having penetration rate higher than 0.35. Similarly, 5% of the sections classifies as "fair" have a penetration rate higher than 1.5. Hence, it is concluded that penetration rate of 0.35 and 1.5 can be used as reliable limits between poor, fair and good drillability classes.

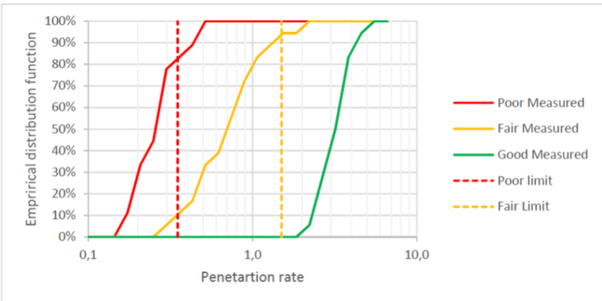

Figure 5. Empirical distribution of penetration rate

Considering all other drilling parameters, a Drillability classification chart developed (Figure 6). These results are based on 107 pile from two job site.

Drillability	Penetration rate values (m/min)		Typical drilling parameters associated with the drillability class			What limits penetration
	Min	Max	Working pressure (bar)	Torque (%)	Number of rotations NR (U/min)	
1 - GOOD	1,5	-	80 - 240	10% - 50 %	25 - 30	Penetration rate is not limited by the ground.
2 - FAIR	0,35	1,5	200 - 260	30 % - 65%	20 - 30	High vertical force -> rig tilts back -> blocked by automatic system
3 - POOR	0	0,35	240 - 300	40 % - 100 %	15 - 25	Max working pressure cannot maintain 30 RPM -> drill bit rotate slower

Figure 6. Drillability classification chart

Our analysis showed that the production rate drops dramatically, if more than a few meters of the pile is classifying as poor. In case of the pile presented in Figure 6:

- 9.0 m of the pile length classifies as good and fair drillability. The corresponding drilling time is 5.3 min
- 1.0m classifies as poor drillability. The corresponding drilling time is 12.2 min

In this case 70% of the drilling time needed to penetrate the 1.0m thick poor zone. This shows that total drilling time, and consequently cost of a pileing highly effected by the drillability. In order to predict drilling times, piling productivity, and piling cost, the drillability needs to be understood.

3.3. Understanding drillability

The results of the statistical analysis are compared with the experience from drill rig operators and theoretical considerations. The background of the penetration rate is the following:

- "Good": Penetration rate is governed by the max RPM (app. 30 in 1st gear). Penetration rate is limited by crowd pull force.
- "Fair": High crowd pressure is needed, rig tilts back. If rig verticality deviate from the vertical by more than 1deg, an automatic system stops crowd push. Meaning the penetration is stopped while the tool is rotating in the ground. In "fair" layer, the drill bit pick up ground from below the drill bit, and compact it on the side of the drill bit. Once the ground loosens below the drill bit, the rig tilts back and crown push is again available. Penetration rate is limited by the time when the crowd push is blocked.
- "Poor": Crowd push is limited as in "fair" conditions. Max working pressure cannot maintain 30 RPM, to achieve higher torque RPM is decreasing. Drill bit rotates slower, so more time is required to allow the ground loosening below the drill bit, and the machine tilts back. More time is spent with the rotation without crowd push. Hence, penetration rate drops.

The "fair" layer is related to the toe of the drill bit, when the vertical resistance of the soil increases, and the drill rig starts to tilt back.

The "poor" yet, seems to be mainly due to the shaft of the drill bit, the main strain is the friction around the drill bit, the torque is consequently getting low.

As discussed earlier, the penetration rate drastically drops at poor drillability. Fair drillability is considered by the authors as an indication of load-bearing ground is reached. Hence, fair drillability is not to be avoided. The biggest differentiator between fair and poor drillability is the required torque to rotate the drill bit in the ground. Figure 7 illustrates this explanation.

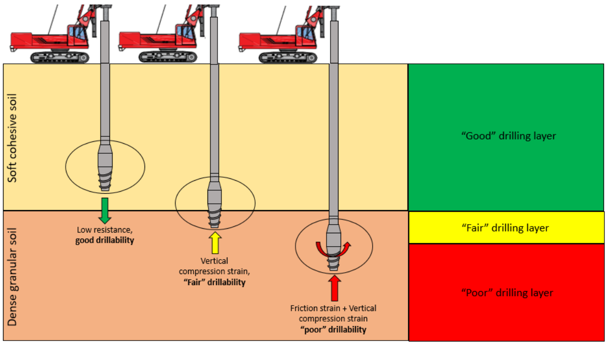

Figure 7. Drillability classes

4. Correlation with CPT testing

In Hungarian practice CPT testing is the most common ground investigation technique for pile design. The pile capacity calculation is based on CPT results. Therefore, CPT testing results were selected as the measure characterizing the ground drillability, as well. A correlation between drilling parameters and CPT results is presented here.

4.1. Identification of "fair" drillability

Drilling records in the vicinity of CPTs are identified. As presented in the previous section the fair layer is indicated by the tilting back of the rig. It is assumed that this process is governed by the ground properties directly at the tip of the drill bit. Hence, the governing ground property is q_c (cone resistance). Limited correlation between friction ratio (Fr) and depth of "fair" layer was found.

Depth of the fair layer was identified on the drilling logs. After that, the cone resistance in the same depth was determined. The average cone resistance is 15 MPa at the depth where the fair layer begins. Results were applicable for all 3 pile diameters (SS33/50, SS43/60 and SS53/70). As the validation of the results 20 CPT, 107 data point from 2 projects was gathered. The first project is located near Jászfényszaru, the second is near Kecskemét, both are located at the central part of the Great Hungarian Plain. The soil is consist of 2-5 meter thick layers of soft clays and competent granular soils (sands and gravely sands, see Figure 8).

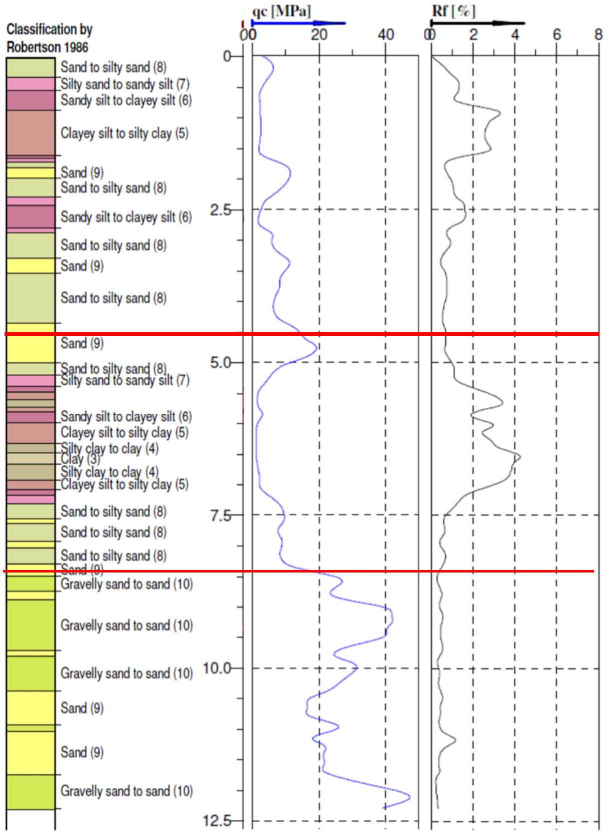

Figure 8. CPT from the site near Kecskemét

The depth where cone resistance exceeds 15 MPa was calculated, see red line in Figure 8. The piles in the vicinity of the CPT-s are identified, and the depth of the fair layer was calculated. The correlation of the CPT based prediction and the actual results can be seen in Figure 9. Actual depth of the "fair" layer is determined based on the drill logs. A strong correlation was found. Most of the actual observation deviates less than 1m from the predicted. The results are valid for depth ranges from 3 meters to 15 meters.

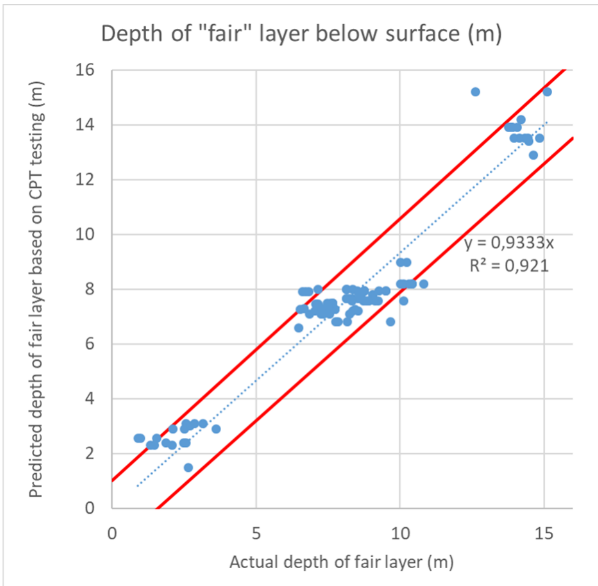

Figure 9. Depth of "fair" layer below surface: correlation of measured and calculated results.

4.2. Identification of "poor" drillability

The required drilling torque is the governing measure where drillability classifies as "poor" (as described in Section 3.3). The rotational resistanc during screw displacement auger penetration in non-cohesive soils depend on soil strength properties (expressed by CPT Cone resistances q_c and Friction ration F_r), auger geometry, and screw technique (the velocity of rotation and penetration). The gravel content of the soil is a key factor in the rotational resistance. Hence friction ratio is also investigated in this section. The total value of torque *MT* generated by screwing process can be divided into two components: *MTs* – moment resulting from soil friction around the auger shaft and *MTb* – moment resulting from soil resistances under the auger base [8].

The soil strength is being characterized by the average cone resistance and friction ratio along the drill bit. To calculate an average cone resistance, the coefficient of auger shape influence η_2 was introduced by Krasińsk [8]. As presented in Figure 10, the shape function depends on the diameter and length of the drill bit.

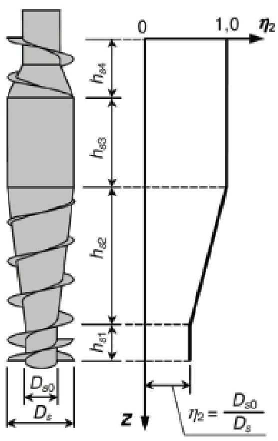

Figure 10. Shape function [8]

Considering the shape of the SS43/60 drill bit, the shape function was created (Figure 11). The diameter of the drill bit varies along the length (see Figure 1). The auger diameter influences the friction at a given depth. It is assumed that the bigger the diameter, the higher the ground resistance is. Also the auger diameter is proportional with the resistance. In order to consider the shape of the auger, a shape function is introduced.

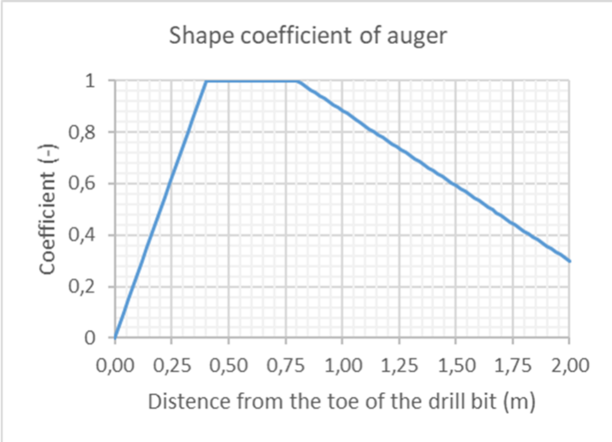

Figure 11. Shape coefficient of auger over a 2 meters drill bit

Once this function is created, it is multiplied with the CPT values to create an average cone resistance, average shaft friction and the average friction ratio (Figure 12).

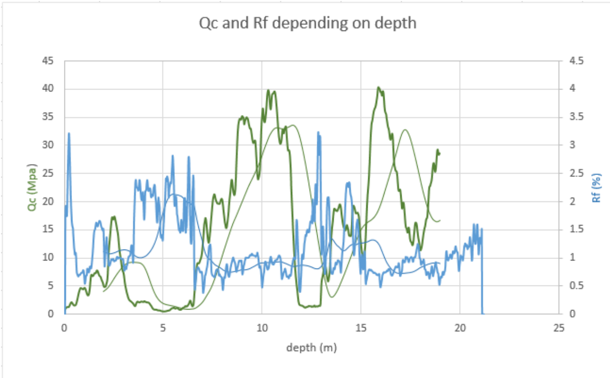

Figure 12. *q_c values (green) and R_f values (blue) – thin curves are the averaged, thick ones the measured*

It can be observed in the figure, that the averaged cone resistance is somewhat smoothened compared to the measures, since it is a sum of resistance along an app. 2.0m long drill bit. Also, there is a shift in the peaks also, since the ground resistance increase when the thickest part of the bit reaches the dense layer (approximately 1-1.5m above the toe of the drill bit).

Depth of the poor layer was identified on the drilling logs. It was compared to average cone resistance and friction ratio, at the depth of the poor layer. The most important observation is that ground with only an average cone resistance of 10-12 MPa may classify as poor, if the ground is gravely. If the ground does not consist at least 20% gravel, then the drillability of the ground classify as Fair even if the average cone resistance is 20-30MPa.

There was no poor layer encountered for small diameter SS pile. Probably the rig torque is sufficient for the smaller diameter drill bit. The experiences were summarized in the table above. Robertson's category of soil is based on the ground classification presented in [10].

Category of soil	Good or Fair	Good or Fair	Poor
qc at the toe of the drill bit (MPa)	<15	>15	>15
average qc along the drill bit (MPa)	*	0-12	>12
average Rf along the drill bit(%)	*	>0.9	0-0.9
Robertson´s category of soil	1-8, 11, 12	2-9	8-10
Corresponding soil	Loose sand or gravel, soft clay or silt	Any soil but Gravel to Sand	Gravel to Sand
Average Gravel content based on	*	0 - 20 %	> 25 %
*: Not relevant			

Figure 13. CPT test results correspond to drillability classes

5. Case study – application in practice

There are two aspects of the research is detailed here:

- How well the results of CPT based drillability analysis correlate with site experience?
- How can the drillability analysis fit into the design optimization?

A piling project near Jászfényszaru is under consideration here. Screwsol piles were selected as deep foundation for the new factory hall. It is a prefabricated reinforced concrete structure. The soil is river deposit, 5-8m of soft clay and competent dense gravely sand. Piles penetrate to the gravely sands. The fair layer is associated with the gravely sand layer. The depth of the fair layer was estimated based on CPT testing. After the completion of piling under the pillars, the drilling data was analyzed. A comparison was made and visualized in Figure 14.

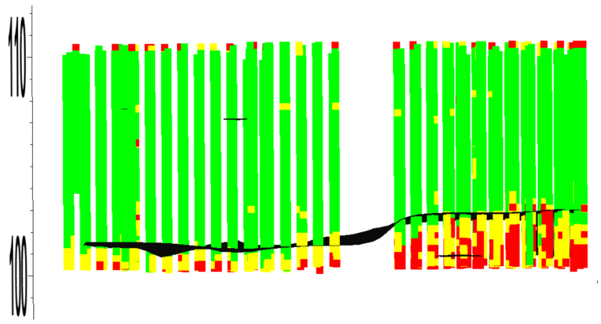

Figure 14. Comparison of predicted and actual depth of "fair" drillability; black: predicted based on CPT; actual drillability: green: "good", yellow: "fair", red "poor"

As one can see, there is a good correlation between the estimated and the actual depth of the fair layer. This result allows practitioners to understand the ground conditions better and optimize pile design.

The next question is how can the drillability analysis fit into the design optimization? For example, if there is a need to penetrate 2-3m to a poor layer, then production rate drops. The following design consideration can be made:

- Use the smallest pile diameter. Drillability issues are usually less severe or even minor using the SS33/50 diameter pile.
- Use design regions or areas. Calculate the different pile capacity for the region where competent layer is higher.
- Replace pile with shorter piles. For example, use 5pcs of 8m long piles instead of 4pcs of 9m long piles.
- Prepare for low production rate and high maintenance cost.

Based on these design considerations, several options can be developed. Loadbearing capacity for all option must be sufficient based on the relevant design standard. The cost however may be significantly different. Hence, the cost associated to the different option is to be calculated, and the optimal is to be selected.

In case of the project in Jászfényszaru, the design was made in phases, as the construction was progressing the design was continuously developed. Less than half of the project was designed after the construction of the first phase was finalized. It made possible to analyze site-specific drillability, production rates, material related costs and time related costs. A good balance is found in pile length which contributed to delivering the project on time and with a good financial result.

6. Summary

Drillability of displacement piles were classified based on drilling parameters. The drillability classes were based on observed behavior during drilling. Penetration rates were correlated to the drillability classes allows practitioners to estimate production rates. Drillability classes can be estimated based on CPT testing. The founding of the papers was verified using two projects.

Identifying drillability classes helps avoid pitfalls of low production and high wear of the tools. Hence it contributes to deliver projects in time and in budget.

Drillability classes are based on the drilling rig behavior (rig tilt back, maximal torque of the rig). It allows a good understanding of the relation of the ground and rig performance. Usually, a single parameter is associated with drilling resistance. It is a simple and undoubtably successful approach. Having said that the authors opinion is that a more complex understanding of the drilling processes is helpful to have a good prediction on drilling performance.

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