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Evaluation of SRD methodologies prediction accuracy at offshore wind farms in the Irish Sea

Georgios Perikleous[1], S. Meissl[1], and T. Stergiou[2]

[1] Ørsted A/S, Wind Power, Nesa Alle 1,2820 Gentofte, Denmark.
[2] Ørsted Ltd, 5 Howick Pl, Westminster, London, UK.

ABSTRACT

The installation of monopiles for offshore wind projects in North Europe and around the world remains an important challenge for many projects, which can lead to significant costs. Over the last 40 years, several empirical methodologies for predicting the soil resistance to driving (SRD) have been proposed by different researchers. These SRD methodologies can provide a significant scatter in the prediction accuracy of the pile driving energy and of the number of blows, in different soil types and soil conditions. The current paper presents a comparison of driving methodologies with respect to the back-calculation analysis performed for three neighbouring offshore wind farm projects in the Irish Sea, based on the methodologies most commonly used for projects in the North Sea, namely the Alm and Hamre (2001), Stevens et al (1982) and Toolan and Fox (1977) methodologies. A detailed analysis of the prediction accuracy for each method has been performed with respect to the soil type, soil strength, penetration depth and pile diameter. These analyses provide an outline of the predictability of each method, for the site-specific conditions.

Keywords: drivability; soil resistance to driving; pile installation

1 INTRODUCTION

The installation prediction of monopiles is heavily dependent in the prediction accuracy of the soil resistance to driving (SRD) methodologies. From the back-calculations of pile installation driving records, a significant mismatch between predictions and measurements has been observed across different wind farms in the North Sea.

For the prediction of the soil resistance during pile driving (SRD), numerous methodologies have been developed over the last decades based on empirical evidence from offshore pile installations for Oil & Gas projects. The same methodologies are generally used for installation predictions of monopile foundations for offshore wind projects across the North Sea. The accuracy of three widely used methods, namely Alm & Hamre (2001), Stevens et al (1982) and Toolan & Fox (1977) for the prediction of SRD at three offshore wind farms in the Irish Sea is the focus of the current paper. For this study, driveability back calculations based on the above-mentioned SRD methods are compared, to define possible trends, such as:

1. Accuracy of SRD methods dependent on soil types.
2. Accuracy of the computed total energy for installation.

Therefore, a total of 121 positions have been statistically evaluated at the three wind farms and the general findings are propounded in this publication. One representative position for each windfarm (position A, position B and position C) is expounded as an example for each wind farm in tables and in graphs.

2 OFFSHORE WIND FARM SITES

The windfarms are located in the Irish Sea, about 30 km offshore from Barrow-in Furness, west coast, U.K. (Figure 1).

Figure 1: The wind farms area in the Irish Sea

2.1 Monopile dimensions

The monopile outer diameters at the three projects range from 6.0m to 8.4m. Details about the pile make-up for the three chosen positions are listed in Table 1.

Table 1: Pile details

Position	Top Diameter	Bottom Diameter	Penetration Depth
[-]	[m]	[m]	[m]
A	5.1	6.3	26.4
B	6.2	7.4	24.9
C	5.7	8.4	25.7

2.2 Hammer

As the monopile at position A was installed much earlier than position B and position C, the monopiles are of smaller dimensions and thus a smaller hammer was used. To install the monopile at position A, the hammer IHC S2000 (max. 2000kJ) was used for installation while for position B and C the MENCK 3500S (max. 3500 kJ) was used.

2.3 Geological Settings

The soil types encountered at the OWF sites primarily comprise quaternary marine sands (Relative Density (I_D) ranges from 80-90%) and clays of low to intermediate plasticity (Plasticity Index (IP) ranges from 10-25%) and an intermediate soil type defined as sand\clay facies (IP ranges from 5-15%). Especially the sediments deposited during the Pleistocene epoch are heavily influenced by the glaciations of the Saalian and the Weichselian period, including the interglacial deposits from the Eemian period.

2.4 Geotechnical Profiles

At all three wind farm sites, cone penetration tests (CPT) were carried out for each wind turbine location. Interpreted CPT profiles for example positions A, B, and C are illustrated in Figure 2 and soil parameters are specified in Table 2.

The sands are generally classified as dense, with maximum q_c values in the range of 30 to 35MPa. The clays are generally classified with maximum q_c values in the range of 3 to 20MPa.

Table 2: Geotechnical parameters

Position A

Depth	Type	Unit Weight, γ'	Friction Angle φ_b	Friction Angle φ_u	Undrained Shear Strength $C_{u,b}$	Undrained Shear Strength $C_{u,u}$
[m]	[-]	[kN/m3]	[°]	[°]	[kPa]	[kPa]
0-1.2	CLAY	5	-	-	1-10	3-15
1.2–14.4	SAND	9	41-44	41-46	-	-
14.4-28	CLAY	9-10	-	-	48-563	65-875

Position B

Depth	Type	Unit Weight, γ'	Friction Angle φ_b	Friction Angle φ_u	Undrained Shear Strength $C_{u,b}$	Undrained Shear Strength $C_{u,u}$
[m]	[-]	[kN/m3]	[°]	[°]	[kPa]	[kPa]
0-19.1	SAND	9-11.1	33-46	35-47	-	-
19.1-27.5	CLAY	10.1-11.8	-	-	67-226	80-285
27.5-28	SAND	11.4	39	41	-	-

Position C

Depth	Type	Unit Weight, γ'	Friction Angle φ_b	Friction Angle φ_u	Undrained Shear Strength $C_{u,b}$	Undrained Shear Strength $C_{u,u}$
[m]	[-]	[kN/m3]	[°]	[°]	[kPa]	[kPa]
0-2.65	SAND	9	34	36	-	-
2.65-3.7	CLAY	8.6	-	-	10	13
3.7–13.5	SAND	11.1	42-46	43-47	-	-
13.5-28	CLAY	10.1-12.1	-	-	45-467	53-606

Note: The subscripts $_b$ and $_u$ denote best estimate and upper bound soil parameters respectively.

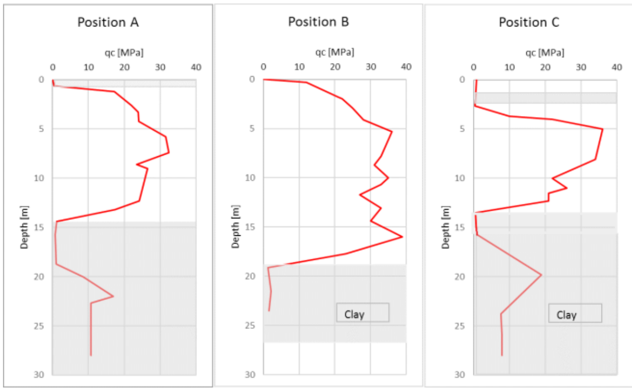

Figure 2: Interpreted qc profiles for position A, B, and C.

3 SRD METHODS

3.1 Toolan and Fox (1977)

The original proposed method by Toolan and Fox (T&F), was developed based on the pile installation of the Graythorpe II jacket at the BP Forties field. The pile diameters used for the development of the method were 54 inches outer diameter piles. The shaft friction of the SRD in clays is equal to the remoulded undrained shear strength of the soil. For sands, the pile shaft resistance is calculated based on the cone penetration resistance, q_c. Tip resistance for both clays and sand is equal to the cone penetration resistance, q_c.

For unplugged piles, as in the case of monopiles, the skin resistance is calculated along the inner and outer pile diameter, and tip resistance is applied on the pile annulus area.

3.2 Stevens et al. (1982)

The Stevens et al. methodology (ST) was developed by evaluating 52 piles at 15 different offshore sites at the Arabian gulf, with pile diameters ranging from 36-42 inches. The SRD calculation in clays is based on the over-consolidation ratio (OCR) for the pile shaft resistance, while the tip resistance is calculated according to API (2011). For non-cohesive soils both shaft and tip resistances are calculated according to the API (2011) bearing capacity formulations.

For unplugged piles, as in the case of monopiles, the skin resistance is calculated along the inner and outer pile diameter, and tip resistance is applied on the pile annulus area.

3.3 Alm and Hamre (2001)

The Alm and Hamre (2001) methodology (A&H) was developed based on the previous work of the writers (Alm and Hamre, 1998) that included the friction fatigue concept (first presented by Heerema, E.P, 1980) for the calculation of the pile shaft resistance. For the methodology development a database of 178 piles from 18 different jacket structures at the North Sea were used. The database pile diameters ranged from 72 to 108 inches and pile penetrations extended up to 70m. According the methodology the SRD, for both cohesive and non-cohesive soils, is calculated based on the cone penetration resistance, q_c.

4 BACK CALCULATION

Back-calculations were performed with the use of the wave equation analysis program GRLWEAP (Pile Dynamics, 2010), that is used to analyse the ENTHRU (energy through) energy propagation from the hammer impact in the pile soil system. During the wave propagation analysis, the total driving resistance experienced by the pile is analysed in a static and a dynamic component as proposed by Smith (1960). The static resistance is calculated according to the different SRD methodologies, as those were previously explained. The dynamic component of the pile resistance is developed due to viscous damping mechanisms as well as inertia effects and is modelled in GRLWEAP with the use of damping factors, which are SRD formulation specific. The damping factors for toe and shaft resistance for each of the three formulations, as used for this analysis are presented in Table 3.

Table 3: Damping values (s/m).

		Toolan and Fox	Stevens et al	Alm and Hamre
		Damping (s/m)		
Clay	Shaft	0.65	0.1	0.25
	Toe	0.5	0.5	0.5
Sand	Shaft	0.16	0.27	0.25
	Toe	0.5	0.5	0.5

Back-calculation analysis of the pile installation was performed by adjusting the hammer stroke height so that the driving energy used during installation, as recorded in the driving log is correctly modelled.

5 COMPARISON METHODOLOGY

The evaluation of the SRD methods was performed for best estimates and upper bound prediction, by comparing statistically the recorded blow counts and hammer energy from the monopile driving log to the back-calculated driving prediction.

For the evaluation, similar soil conditions were identified and grouped so that a straight comparison of the prediction accuracy could be performed.

Soil categories were defined based on average q_c, c_u or φ values, following a naming convention, defined by:

A [Avg. value] - D [Max-min delta value]

Variable A describes the general magnitude of soil strength, variable D gives the delta max-min of the soil strength values q_c, c_u or φ value, which depicts the general magnitude of soil strength value shift. A graphical example is given in Figure 3.

This categorization was done for:

1. 5m depth intervals, and
2. along the full pile penetration length.

By defining the above-mentioned categories, different positions can be compared based on their soil type and strength. The defined categories are used as input for crosscheck the SRD methodology prediction accuracy, based on soil strength values (from low values, low shifts to high values, high shifts).

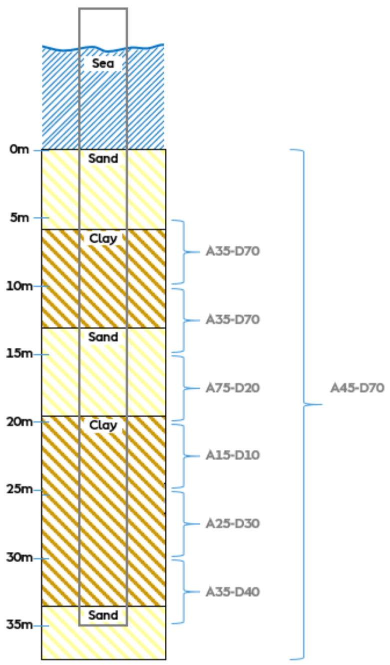

Figure 3 Example for q_c naming categories.

The presented positions A, B and C contain: 5m categories between A10-D05 and A35-D40, with an overall category of A25-D50.

6 RESULTS

6.1 Accuracy of SRD methods

Using the comparison methodology, optimal performance areas for the three different SRD methods could be defined based on the soil conditions. In shallow dense sands, A&H and T&F shows a tendency to overestimate the SRD correlated to q_c ≥30 MPa (Figure 4). Sand layers of the same values but in depths greater than 10m show a good fit for both methods. For deeper dense sand layers, the tendency of overestimating the SRD tends to appear for q_c >50MPa and increases with increasing q_c. T&F appears to be less sensitive to q_c variations compared to A&H. In general, T&F upper bound closely follows the A&H best estimate trend. Compared to those two methods, ST method shows the worst fit. In sands, a general trend is visible, where the deviation decreases as the friction angle, φ increases. This trend is magnified as the depth is increased.

For clays, all methods have the tendency to under estimate the SRD for q_c <3MPa and c_u <80kPa (Figure 4, position A, 15–20m and B > 19m). For clays, with qc >20MPa and c_u ≥500kPa and above, the A&H as well as the T&F method start to overestimate the SRD (Figure 4 - position A, >23m and C >20m). With the increase of depth and q_c values, A&H's tendency to over predict the SRD increases as well. Again, T&F appears to remain more stable. The ST tendency to under-estimate the SRD in stiff clays decreases with increasing depth and c_u values.

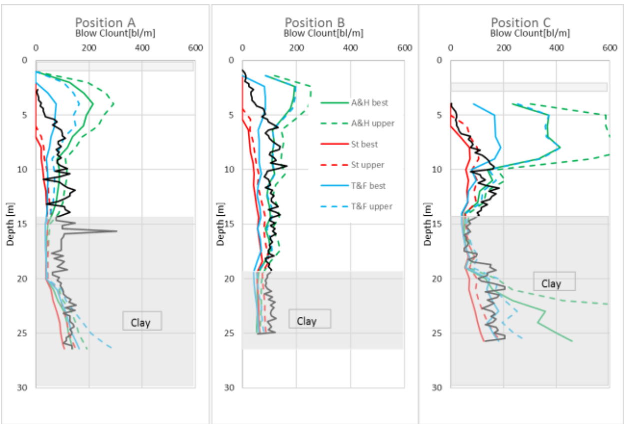

Figure 4: Blow count curves

6.2 Accuracy of the computed total energy

From Figure 5 it is visible that for position A, all best estimate approaches under-predict the total amount of energy, when compared to the energy recorded during installation. The best fit is provided by the A&H method, whereby ST under-predicts the total energy, showing a mismatch of more than 50%. This tendency decreases from A to C, finally showing at position C that three out of six approaches over-estimate the energy (T&F upper bound as well as both A&H approaches). Only T&F best estimate predictions provide a good fit compared to the recorded total energies. ST still under predicts the total energy, but especially ST upper bound comes closer at positions C than for position A.

When predicting the total amount of energy, a general trend of decreasing mismatch with increasing diameter is observed, as the diameter at the offshore wind farm range from min. 6.0 m at position A to max. 8.4 m, at position C.

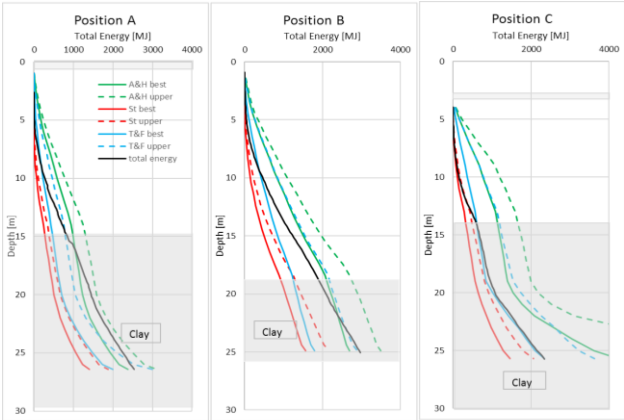

Figure 5: Total energy curves

7 DISCUSSION & CONCLUSION

The study shows that CPT based SRD methods performed satisfactorily for a certain range of soil resistance but over-estimate SRD for q_c≥50MPa. This tendency seems to be depth sensitive as well. Moreover, the A&H method appears to be more sensitive to q_c variations than the T&F method. This might be explained by the original CPT database used to develop this empirical formulation. The ST method, which is only based on lab-data, under-predicted the SRD by about 50% and it can therefore be postulated that it should be used with caution when used for SRD prediction for monopiles, in similar soil conditions.

Overall, a general trend of decreasing mismatch with increasing diameter was visible. Other possible explanations could be a general geometry impact, like d/t ratio or increase in dimensions of the conical part of the monopiles, which will be part of further investigations.

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