AN ASSESSMENT OF THE ACCURACY OF SRD METHODOLOGIES FOR OWF MONOPILE INSTALLATION AGAINST A NORTH EUROPE DRIVING RECORDS DATABASE

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ABSTRACT

As monopile foundations diameter scales up with the larger turbines and increasing water depth, installation feasibility is becoming a greater risk in the offshore wind industry. Experience has shown that current drivability methodologies miscalculate the soil resistance to driving (SRD) when compared to actual driving data, resulting in additional installation costs and overestimation of pile fatigue. For the current study, two hundred sixty (260) driving logs from four offshore wind farms (OWF) in different areas of the North Sea have been selected and back calculated using standard industry SRD methodologies, namely Alm & Hamre (2001), Toolan & Fox (1977) and Stevens et al. (1982). The investigated pile driving records cover a broad range of soil conditions both in terms of soil type (sand dominated, clay dominated and layered soil profiles), soil strength (easy to hard driving conditions), monopile diameters and penetration depths. The accuracy of each method has been quantitatively evaluated, with the results underpinning the industry concern of the inadequacy of the existing SRD formulations to predict the drivability of OWF monopiles and illustrating the need for development of new SRD methodologies, tailored to the Offshore Wind industry.

Keywords: pile driving, back-calculation, statistical analysis, offshore wind farms

INTRODUCTION

The last decades have seen a steadily increase of the global offshore capacity, standing at 23GW, with 80% of this based in Europe. Approximately 150 new offshore projects are expected completion within the next 5 years, according to IEA (2019). The agency forecasts that global offshore wind power capacity is set to increase 15-fold over the next two decades. Monopile (MP) is the preferred foundation type for wind turbine generators (WTG) in the great majority of offshore wind farm (OWF) developments in the North Sea and around the globe. Over the last two decades thousands of monopile foundations with diameters up to 8.4m (27,6ft) and embedment length to diameter ratio (L/D) typically between 2 to 6 have been installed by dynamic impact driving.

Pile installation is a significantly costly operation that could represent between 4% to 10% of the total construction capital cost (CAPEX) of an OWF (Noonan, 2018) and costs can quickly soar if remediation operations are required in case of pile driving refusal. Unplanned mobilization of drilling equipment spreads can be considerably lengthy and complex. Additionally, contingency mobilization of drilling equipment spreads will add superfluous costs to the project if the equipment is unused during the project execution.

Therefore, accurate and reliable driveability predictions are of paramount importance, particularly when considering the monopile of the future, with increasing diameters and smaller diameter to wall thickness ratio (D/t). Driveability will be a key aspect determining the feasibility of the monopile concept for future OWF development sites.

Wave equation analysis

A driveability study is normally performed based on the wave equation analysis theory introduced by Smith et al. (1960). Smith et al. (1960) analysed the pile driveability procedure based on the 1D elastic stress wave propagation model, where the pile is modelled as a series of lump masses and interconnecting springs, while the soil resistance to driving is modelled as a series of springs and dashpots at the pile shaft and tip (see Fig. 1).

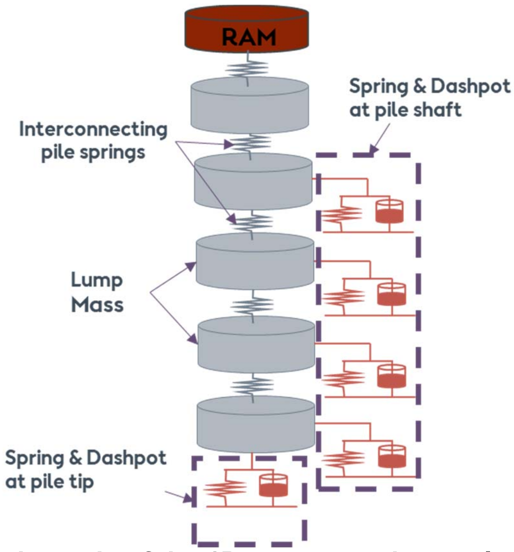

Fig. 1. Schematic of the 1D wave equation analysis model.

The prediction accuracy of the driveability analysis is heavily dependent on the adopted SRD model.

SOIL RESISTANCE TO DRIVING

Soil resistance to driving has been studied since the end of the 1970s by numerous researchers based on the back-calculation analysis of pile driving installation records. The great majority of these studies has been based on analysis of the installation records of offshore jacket platforms of oil and gas (O&G) development projects in the North Sea and in other places like the Gulf of Mexico, the Persian Gulf and West Africa.

Most notably, Toolan and Fox (1977), Heerema et al. (1978), Semple and Gemeinhardt (1981), Alm and Hamre (1998), Alm and Hamre (2001) and Byrne et al. (2012) proposed different SRD methodologies based on the study of piles installed in the North Sea. Stevens et al. (1982) proposed an SRD methodology based on data from pile installations in the Gulf of Mexico and the Persian Gulf. Similarly, Dutt et al. (1995) proposed an SRD methodology for piles installed in normally consolidated clays in the Gulf of Mexico. Puech et al. (1990) and Colliat et al. (1993) studied the driving records of pile foundations installed in the Gulf of Guinea and offshore Angola, respectively. Finally, Schneider and Harmon (2010) proposed a methodology for analysing the driveability of open-ended piles in dense sand based on the analysis of pile installation records from developments in Japan, USA and the Netherlands. It is important to note that to date an SRD methodology specifically tailored to monopiles such as the ones used in the Offshore Wind industry is yet to be developed.

Piles used for O&G jacket structures when compared to offshore wind MP foundations are considerably smaller in diameter, typically 1,07m (3.5ft) to 2.74m (9ft) compared to the 6m (19.7ft) to 8m (26.2ft). As such, it is paramount to evaluate the applicability of the existing SRD methods for pile drivability analysis of OWF monopile foundations.

SRD methods analysed in the current study

For the back-calculation analysis, three SRD methods widely used for pile drivability analysis in the North Sea were considered in this paper. Namely, the methods proposed by Alm and Hamre (2001), Toolan and Fox (1977) and Stevens et al. (1982).

The methodology proposed by Alm & Hamre (2001) was based on the analysis of driving records form 178 piles from 18 different jacket structures installed in the North Sea, with pile diameters ranging from 1.83m (6ft) to 2.74m (9ft). The proposed methodology incorporates the concept of friction fatigue, first introduced by Heerema (1981). As an input parameter for the SRD calculations, the authors proposed the use of cone penetration test (CPT) tip resistance (q_c) and sleeve friction (f_s), and the constant volume friction angle (δ).

The Toolan and Fox (1977) methodology was developed by evaluating the installation records of the 1.37m (4.5ft) diameter piles of the Graythorpe II jacket at the BP Forties oil field in the UK sector of the North Sea. For the calculation of the SRD, the authors proposed the use of the CPT cone tip resistance (q_c) for the calculation of the shaft friction in sands and the tip resistance in sands and clays. For the shaft resistance in clays, the use of the remoulded undrained shear strength ($c_{u,r}$) was suggested.

Finally, the Stevens et al. (1982) method was developed by analysing pile installation records from 15 offshore sites at the Persian Gulf, based on the axial bearing capacity for approach of API (2000). A total of 52 piles with diameters ranging from 0.91m (3ft) to 1.07m (3.5ft) where analysed. The authors adopted the Semple and Gemeinhardt (1981) methodology of associating SRD with the over consolidation ratio for the calculation of the pile shaft resistance in cohesive soils. For the SRD calculation in cohesionless soils the proposed methodology is mainly based on the API bearing capacity formulation.

ØRSTED'S PILE INSTALLATION DATABASE

Ørsted's pile installation database comprises high quality installation data from more than 600 monopiles, installed in the North Sea as part of the development of more than ten offshore wind farm projects. For the evaluation of the accuracy of the SRD methods in the current study, four offshore wind farm projects from different areas in the North and Irish Sea were selected. The analysed positions were selected so that these would cover a broad range of soil conditions in terms of soil type (sand dominated, clay dominated and layered soil profiles), soil strength (easy to hard driving conditions) monopile diameters, penetration depths and driving energy. The general areas where the wind farms are located are presented in Fig. 1.

Project 1 and Project 2 are neighbouring sites at the south sector of the North Sea, Project 3 is situated in the Irish Sea and finally, Project 4 is located in the UK east coast.

A total of 260 monopile driving records were analysed in this study. Pile diameters analysed ranged from 5.90m to 8.10m as presented in Table 1.

Fig. 2. Wind farms location in the North Sea

Table 1. Monopile bottom diameter and hammer per project

Project	Pile outer diameter (OD) (m)	Hammer
Project 1	5.90	IHC-S2000
Project 2	8.00	IHC-S3000
Project 3	7.10	MHU-3500S
Project 4	8.10	IHC-S4000

SOIL DATA

The soil profiles at the selected projects consisted predominately of sand and clay layers, with interbedded sand and clay layers encountered at some locations.

Project 1 and Project 2

The soil types encountered at the site of Project 1 and Project 2 primarily comprise marine and tidal post glacial (Holocene) deposits, marine and meltwater late glacial deposits and meltwater glacial deposits. Sand sediments are prevailing over the entire investigated depth at the two sites with varying grain sizes from fine to coarse. Within these sands, fine grained sediments of silt and clay are interbedded at different depths and with variable thicknesses. Exception to the latter being the glacial meltwater deposits, which are clay-free.

Project 3

The soil types encountered at Project 3 primarily comprise marine post glacial deposits (Holocene era) and glaciomarine and subglacial (Pleistocene) deposits. The soil types encountered across the site are mainly fine to coarse grained sands, clays of low to intermediate plasticity and an interbedded sand and clay layer.

Project 4

The soil types encountered at the Project 4 site primarily comprise of loose to very dense sands and firm to very stiff clays of fluvial to marine deposits (Holocene) to non-marine, fluvial to deltaic (Lower Pleistocene) deposits. Channel infills of subglacial to shallow marine deposits are encountered across the site. Sand deposits are uniformly graded, silty fine to medium grained occasionally gravelled, while clays are low to high plasticity.

Table 2 presents the range of the soil parameters accounted for in the back-calculation analysis for each of the projects.

Table 2. Soil strength parameters ranges per project

Project	q_c (MPa)	f_s (kPa)	φ' (°)	c_u (kPa)
Project 1	0.4-80.0	10-900	28-41	40-310
Project 2	0.2-89.0	1-957	31-46	20-950
Project 3	0.5-70.0	2-1500	26-46	14-813
Project 4	0.1-89.5	1-2240	31-43	32-727

q_c - CPT tip resistance
f_s - CPT sleeve friction
φ' - internal angle of friction
c_u - undrained shear strength

BACK-CALCULATION ANALYSES

Driveability back-calculations were performed using a wave equation analysis program (WEAP) based on the methodology proposed in the classic paper of Smith (1960). For the back-calculation analyses the adapted stroke method was used, i.e. adjusting the hammer stroke height to fit the recorded energies of the driving log and calculating the corresponding blow counts per driving step (see equation [1]).

$$h_{stroke} = E_{stroke} \frac{h_{max}}{E_{max}} \quad [1]$$

Where h_{stroke} (m) is the adjusted hammer stroke height, E_{stroke} (kJ) is the energy of the analysed stroke as indicated in the driving log, h_{max} (m) is the maximum hammer stroke height and E_{max} (kJ) is the maximum nominal hammer energy.

The SRD was calculated from each of the three aforementioned methodologies. The corresponding damping and quake values of each method used for the wave equation analysis, are presented in Table 3.

Table 3. Damping and quake factors used for back-calculation analyses

		Toolan and Fox		Stevens et al		Alm and Hamre	
		Quake (mm)	Damping (s/m)	Quake (mm)	Damping (s/m)	Quake (mm)	Damping (s/m)
Clay	Shaft	2.5	0.65	2.5	0.1	2.5	0.25
	Toe	2.5	0.5	2.5	0.5	2.5	0.5
Sand	Shaft	2.5	0.16	2.5	0.27	2.5	0.25
	Toe	2.5	0.5	2.5	0.5	2.5	0.5

The SRD was calculated in all cases based on the best estimate soil profile parameters, assuming an unplugged pile behaviour.

SRD METHOD EVALUATION APPROACH

To evaluate the performance of each SRD methodology the predicted blow counts calculated from the adapted stroke back-calculation were compared to the recorded blow counts. In order to quantify the accuracy of the methods, the root square mean deviation (RSMD) of the calculated and recorded blow counts were calculated as per equation [2].

$$RSMD = \sqrt{\frac{\sum_{i=1}^{n}\left(BLC_{rec,i} - BLC_{calc,i}\right)^2}{n}} \quad [2]$$

Where $BLC_{rec,i}$ = recorded blow count number at depth i, $BLC_{calc,i}$ = calculated blow count number at depth i, n = the number of penetration steps. Furthermore, the normalized root square mean error (NRSMD) was calculated for each position, by dividing the RSMD by the recorded average blow count of the driving-log (see equation [3]) so that a direct comparison between different positions could be done.

$$NRSMD = \frac{RSMD}{\overline{BLC}_{rec,avg}} \quad [3]$$

Where $\overline{BLC}_{rec,avg}$ is the average blow count of the driving-log. NRSMD = 0 indicates an absolute match between the recorded and calculated quantities.

Anusic (2018) suggested the use of the NRSMD parameter as metric to quantify the accuracy of each SRD method. The following categories are adopted from Anusic (2018) to classify the match quality of the back-calculation analysis based on the value of NRSMD:
0 < NRSMD ≤ 0.5 designates a good match, 0.5 < NRSMD ≤ 1.0 a poor match, 1.0 < NRSMD ≤ 10.0 a very poor much and finally NRSMD > 10.0 signifies an unacceptable match. Figure 2 presents examples of what constitutes a good, poor, very poor and unacceptable match

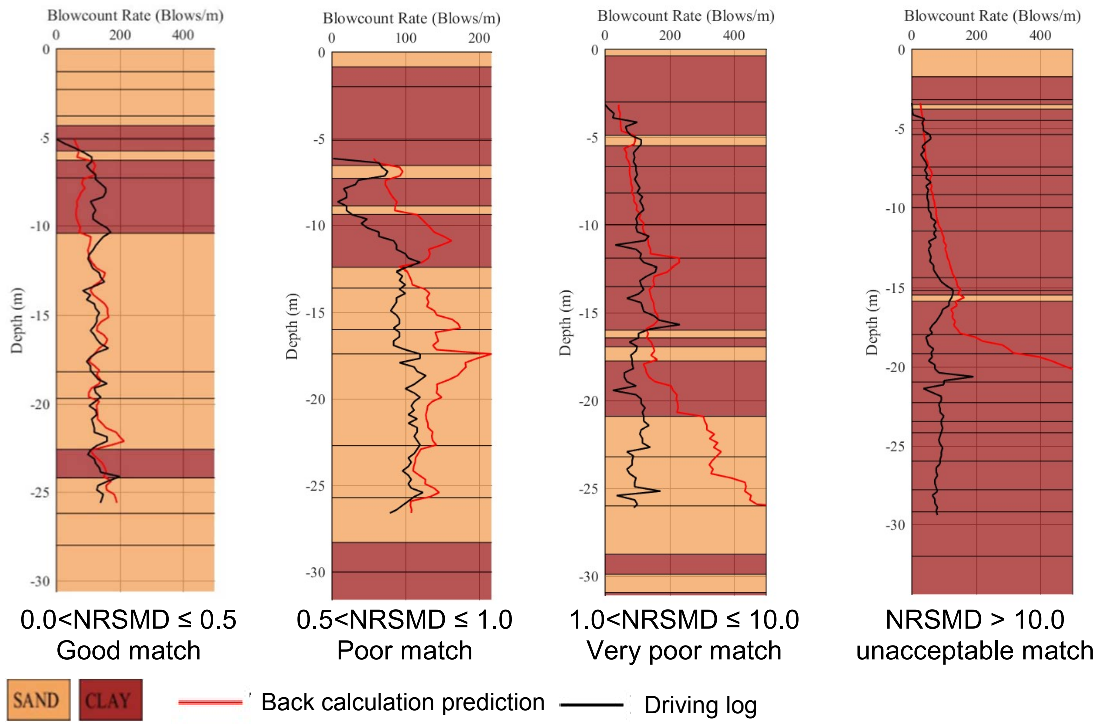

Fig. 3. Categories of back-calculation analysis match quality based on NRSMD value.

RESULTS

The accuracy of each of the SRD methods was analysed for each of the four projects by calculating the respective NRSMD. From the distribution of the percentage of positions across the four categories presented in Fig. 4 the suitability of each method can be evaluated. The Toolan and Fox (1977) method has the highest prediction accuracy as 59% of the positions fall in to the Good match category, while Alm & Hamre (2001) has the lowest percentage of positions (40%) that provide a good fit. Overall, all methods provide very poor to unacceptable predictions, with a considerable share (33% to 43%) falling into the poor match category.

The mean NRSMD (μ_{NMRD}) value for the three methods as well as the standard deviation (σ_{NMRSD}) are presented in Table 4. Furthermore, the coefficient of variation (CoV) is also presented, with CoV = μ_{NMRD} / σ_{NMRSD}.
To avoid possible skewing of the results, due to high NRSMD values caused by pile refusal predictions, a maximum NRSMD value of 10 was considered for the calculation of the statistical parameters.

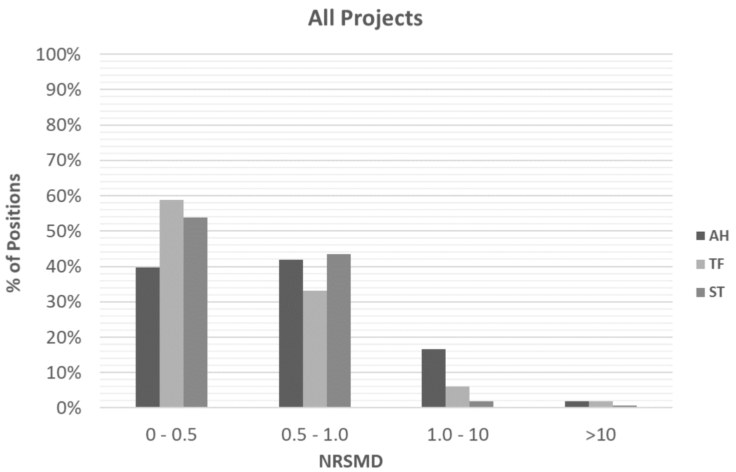

Fig. 4. Normalized mean root squared deviation of all projects for Alm & Hamre (AH), Toolan & Fox (1972) and Stevens et al. (1982).

An evaluation of the suitability of the different methods for the four projects analysed, can be done by looking into μ_{NRSMD} and CoV for each method. The smallest these two parameters are the more accurate and consistent predictions the method provides. All three methods provide a mean NRSMD value higher than 0.5, i.e. generally yielding poor predictions; furthermore, the three methods have a relatively high CoV which shows that all models have a big dispersion in their prediction accuracy.

Table 4. Assessment of SRD method for all analysed piles

Method	Mean (μ_{NRSMD})	Standard Deviation (σ_{NRSMD})	CoV
Alm and Hamre	0.72	0.91	1.27
Toolan and Fox	0.65	1.22	1.87
Stevens et al.	0.57	0.65	1.14

The NRSMD distribution for each of the projects analysed is presented in Fig. 5. As it can be observed the prediction behaviour of all methods is significantly project dependent.

All three methods perform better in Project 1 and Project 2, where no unacceptable results are observed, and only limited very poor match predictions are observed. The two projects are in adjacent sites with similar soil conditions, but considerably different pile diameters.

At Project 1, 5.9m diameter monopiles were installed while in Project 2, 8.0m diameter monopiles. As it can be observed from the NRSMD distributions (Fig. 5.a and Fig. 5.b) and from the μ_{NRSMD} value in
Table 5 all methods provide similar prediction results, but a slightly higher variation is observed for all methods for Project 2, as the CoV is greater compared to Project 1. From the comparison of the two projects is can be concluded that the diameter increase for monopiles (OD>6m) does not significantly affect the method's accuracy.

For Project 3 all three methods have the poorest performance, with Toolan and Fox and Alm and Hamre having a few positions laying in the unacceptable category, mainly as a result of pile refusal predictions. Both methods provide an μ_{NRSMD}>1 meaning that the majority of the back-calculation analysis provided a very poor match to the recorded data.

For Project 4, Toolan and Fox method shows the best fit with the great majority of the positions having a good match (μ_{NRSMD}=0.5), but with a relatively high variation in the accuracy due to the pile refusal prediction for a number of positions. Alm and Hamre method provides the lowest accuracy.

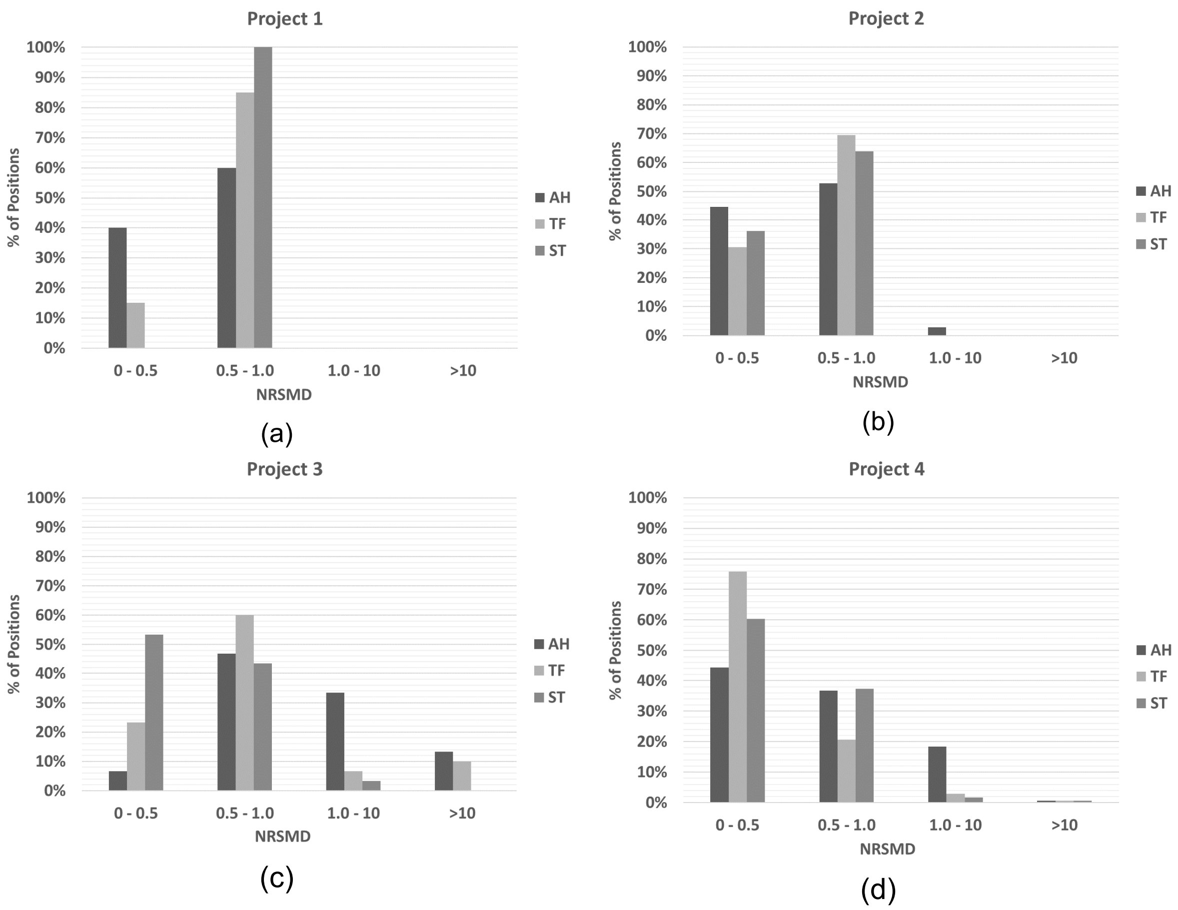

Fig. 5. NRSMD for Alm & Hamre (AH), Toolan & Fox (1972) and Stevens et al. (1982) for four projects analysed. (a) Project 1 (OD=5.9m), (b) Project 2 (OD=8.0m), (c) Project 3 (OD=7.1m), (d) Project 4 (OD=8.1m).

Table 5. Assessment of SRD method for all projects

Project	Method	Mean (μ_{NRSMD})	Standard Deviation (σ_{NRSMD})	CoV
1	Alm and Hamre	0.54	0.09	0.18
	Toolan and Fox	0.60	0.08	0.13
	Stevens et al.	0.69	0.08	0.11
2	Alm and Hamre	0.54	0.21	0.38
	Toolan and Fox	0.54	0.12	0.21
	Stevens et al.	0.56	0.13	0.23
3	Alm and Hamre	2.20	3.09	1.41
	Toolan and Fox	1.67	2.83	1.69
	Stevens et al.	0.65	0.59	0.89
4	Alm and Hamre	0.78	1.07	1.37
	Toolan and Fox	0.50	0.80	1.59
	Stevens et al.	0.55	0.84	1.54

Summary and Conclusion

The installation records of 260 WTG monopile foundations from four projects in the North and Irish sea were back-analysed. The prediction accuracy of three SRD methods (Alm and Hamre, 2001, Toolan and Fox,1971 and Stevens et al., 1982), commonly used in the offshore wind industry for monopile driveability prediction, was evaluated.

For the evaluation of the SRD methods, the normalised mean squared root deviation for each back-calculation analysis was calculated and categorised based on the matching quality with the measured blow counts record. From the evaluation of the matching quality it can be concluded that these commonly used methods, in general, provide a poor match prediction for monopiles with diameters larger than 6m and that the accuracy of the methods is highly depended on the local soil conditions.

The poor prediction accuracy of the existing SRD methods can be attributed to the relatively limited database of driving records that has been used for their calibration, using piles of diameter smaller than the ones used by the offshore wind industry. Moreover, it is equally important to the poor prediction performance that the calibration of the methods has been done for a particular site or regional settings.

The results of this study underpin the industry concern of the inadequacy of the existing SRD formulations to predict the drivability of OWF MP, whilst illustrating the need for development of new SRD methodologies, tailored to the Offshore Wind industry. As demonstrated, such new methodologies need to be calibrated to a larger database of MP installations, covering different geographical areas.

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