An assessment of pile driveability analyses for monopile foundations

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ABSTRACT

Several methodologies to predict the static soil resistance to driving (SRD) available in the literature have found wide use in the offshore industry over the last decades. These range from simple methods that require few soil strength parameters to more advanced semi-empirical methods that correlate the driving resistance to cone penetration test measurements. These methods were primarily developed based on driving records for piles less than 2.5m in diameter i.e. much smaller than the monopiles currently used in the offshore wind industry today. The aim of this study is to evaluate the accuracy of some of the most widely used SRD prediction methods when employed for driveability analysis of large diameter monopile foundations, by comparing the predicted SRD profiles with the driving records of 6.5m diameter monopiles installed in the Danish region of the North Sea.

Keywords: driveability analyses, SRD prediction methods, monopiles, pile run

1 INTRODUCTION

Pile driveability is a major component of the pile design process for the offshore industry, as the selection of a suitable driving system based on preliminary predictions can significantly reduce the pile installation cost. This is becoming increasingly important as the typical pile diameter is rising to accommodate the heavy loads from the increasingly larger wind turbine generators.

Pile driveability analyses evaluate the ability of the pile to be installed with an acceptable risk of early refusal, to reach the designed penetration depth. In cases of early pile refusal, a larger hammer needs to be sourced, causing delays and additional costs. Moreover, in cases of low driving resistances, unexpected pile runs could damage the crane, the steel wires and even cause the loss of the pile and hammer into the sea if no precaution measures are in place. Attention is also paid to the number of hammer blows, which must remain within a reasonable range, to avoid overstressing the steel and causing fatigue damage to the pile. Accurate assessment of the soil resistance during driving (SRD) is key to such predictions, ensuring that a safe installation takes place.

In this study, four SRD prediction methods [Stevens, et al. (1982), Toolan and Fox (1977), Alm and Hamre, (2001) & DNV skirt foundation method (1992)] are assessed for their accuracy in predicting self-weight pile penetrations. Three of the SRD approaches are then employed in driveability analyses of monopiles. Both pile runs and continuous driving cases are examined, and the predicted blow-counts are compared to the measured response, aiming to give guidance for the use of the considered SRD methods for large diameter piles and to suggest appropriate modifications in their formulations.

2 THE SITE

The windfarm examined in this study is situated in the Danish sector of the North Sea, comprising 49 wind turbines, all founded on 6.5m diameter open-ended steel monopiles, with foundation depths between 25m and 32.3m. The facility sits in a water depth between 11m and 19m.

Foundation conditions at the site comprise post-glacial sediments of shallow marine-coastal origin, which can be simplified from a geotechnical point of view to two main geotechnical units. The first unit represents the recent shallow marine depositional environment and is formed by very dense sands of varying thickness, while the second unit reflects the tidal lagoon dominated depositional environment and comprises predominantly sandy silts and clays with local sand lenses.

3 SRD PREDICTION METHODS

During pile driving there are two components constituting the total driving resistance: the dynamic resistance, which is an outcome of inertial and viscous rate effects and the static resistance (Randolph, 2000). The latter is the sum of the shaft friction and the end bearing resistances applied to the pile wall surface and the tip area respectively. Various methods of evaluating the SRD exist in the literature and have found wide use in the industry. Steven's et al. (1982), Toolan and Fox (1977) and Alm and Hamre (2001) are some examples of SRD prediction methods developed through back analysis, using records from pile installations in various soil conditions. These three standard approaches, along with a skirt foundation method proposed in the Danish code of practice (1992), briefly presented in Table 1, are employed in this study for the driveability analyses and the prediction of self-weight pile penetrations.

4 PILE DRIVEABILITY ANALYSIS

During pile driving, each hammer blow generates an elastic wave which propagates away from the point of impact at the pile head, decreasing in amplitude as it travels downwards. Pile driving can be idealised as a wave propagating within a 1-D unconstrained elastic rod. For this study, the software ALLWAVE.PDP (Allnamics), which adopts the Smith model (1960), was used to solve the 1-D analysis problem. The pile is discretised in segments, while the interface condition and far-field response is represented by a linear weightless spring and a plastic slider with a viscous dashpot. The interaction between the pile and the soil is controlled by the linear springs, until the threshold of the plastic slider is reached. The viscous enhancement of the soil caused by rapid strains along the shear zone, is represented by the viscous dashpots, which add to the

Table 1. Summary of main principles of SRD prediction methods.

Method	Origin of the method	Method basic principles	Method formulations – Type of foundation soil: Cohesionless soils	Method formulations – Type of foundation soil: Cohessive soils
Stevens et al (1982)	Back analyses of pile installation records in the Arabic Gulf (pile diameter 0.91m-1.06m)	No CPT based method. Shaft and tip resistance is determined on the basis of the API code (1981) static formulations.	shaft friction: $f_s=K_s \cdot p'_0 \cdot \tan\delta$ end bearing: $q=p'_o.N_q$	shaft friction: $f_s=F_p \cdot \alpha \cdot s_u$ end bearing: $q=9.s_u$
Toolan and Fox (1977)	Back analyses of pile installation records of open-ended steel piles in the North Sea area	CPT based method	shaft friction: $f_s=1/300*q_t$ end bearing: $q=q_t$ (weighted average)	shaft friction: $f_s=s_{u\ res}$ end bearing: $q=q_t$ (weighted average)
Alm and Hamre (2001)	Back analyses of pile installation records of open ended piles in the North Sea (pile diameter 1.8m-2.7m)	CPT based method Friction Degradation Mechanism	Initial shaft friction: $f_{si}=(K_s \cdot \sigma'_{v0} \cdot \tan\delta) \cdot 0.5$ Residual shaft friction: $f_{sres}=0.2 \cdot f_{si}$ Tip resistance: $q_{tip}=0.15 \cdot q_t \cdot (q_t/p'_o)^{0.2}$ Shaft friction: $f_{res}+(f_{si}-f_{res}) \cdot e^{k \cdot (d-p)}$	Initial shaft friction: $f_{si}=f_s$ Residual shaft friction: $f_{sres}=0.004 \cdot q_t \cdot (1-0.0025 \cdot q_t/p'_o)$ Tip resistance: $q_{tip}=0.6 \cdot q_t$ Shaft friction: $f_{res}+(f_{si}-f_{res}) \cdot e^{k \cdot (d-p)}$
DNV skirt foundation method (1992)	Guidelines described in the DNV classification notes for skirt design.	CPT based method	shaft friction: $f_s=k_f \cdot q_t$ end bearing: $f_s=k_p \cdot q_t$	

Legend: K_s:coefficient of lateral earth pressures, p'_o:effective overburden stress, δ:interface friction angle, F_p: dimensionless OCR factor proposed by Semple & Gemeinhardt (1981), α: shaft friction factor, s_u:undrained strength, q_t:cone tip resistance, k: friction degradation factor, d: depth of layer, p: depth of the pile tip.

model a resistance which is proportional to the loading rate. The total soil resistance applied to each element is the sum of the static resistance, modeled by the springs, and the dynamic resistance modeled by the dashpots.

In addition to the information regarding the characteristics of the hammer, the pile geometry, the CPT profile for each location and the SRD prediction methodology, the software requires a set of parameters (quake, damping, alpha factor, yield factor) which accompany Smith's solution. Quake values define the elastic threshold of the spring. When the soil-pile relative displacement exceeds the quake value plastic behaviour is triggered. The damping parameter relates the shaft friction applied to the pile during driving with the velocity of the pile particles. The relationship can be linear or exponential, which is controlled by the alpha factor. The yield factor defines the relationship between the plastic resistance force of a spring in compression and tension. Finally, the hammer delivered energy per blow for 0.25m penetration increments is required so that the analyses results in terms of blow-count can be compared to the measured pile driving response.

Furthermore, in the case of the Alm and Hamre SRD methodology, a modified friction degradation mechanism is also examined. The original model suggests that the residual shaft friction in sands can drop as low as 20% of the initial value. However, this degradation concept yielded SRD results which typically lie below the measured response. Therefore, in addition to the original method, a case was examined where the residual shaft friction was raised to 50% of the initial value.

5 ANALYSIS RESULTS AND DISCUSSION

5.1 Pile run predictions

The SRD prediction methodologies were employed to establish the soil resistance profiles at the wind turbine generators (WTG) locations where pile runs occured. Pile run initiates when the weight force of the pile exceeds the soil resistance. To assess the accuracy of each method in predicting pile runs, the total predicted soil resistance force is compared to the pile and hammer weight force (Fig. 1, Fig. 2 & Fig. 3).

The Alm and Hamre and DNV methodologies yield similar SRD trends, which typically fall below or very close to the weight of the pile in zones where the pile run is well defined and continuous (Fig. 1 & Fig. 2). Furthermore, in locations where pile running is not continuous and clear, but is disrupted by very low blow-counts (Fig. 3), both methods seem to yield very accurate predictions, since the calculated SRD force lies between the pile force and the combined pile and hammer force, reflecting precicely the pile driving sequence.

In order to evaluate the methods examined above in a larger scale, the calculation of the SRD force was undertaken in 17 WTG locations where pile runs were recorded and was compared to pile weight force along the zones where zero blow-count was indentified. The

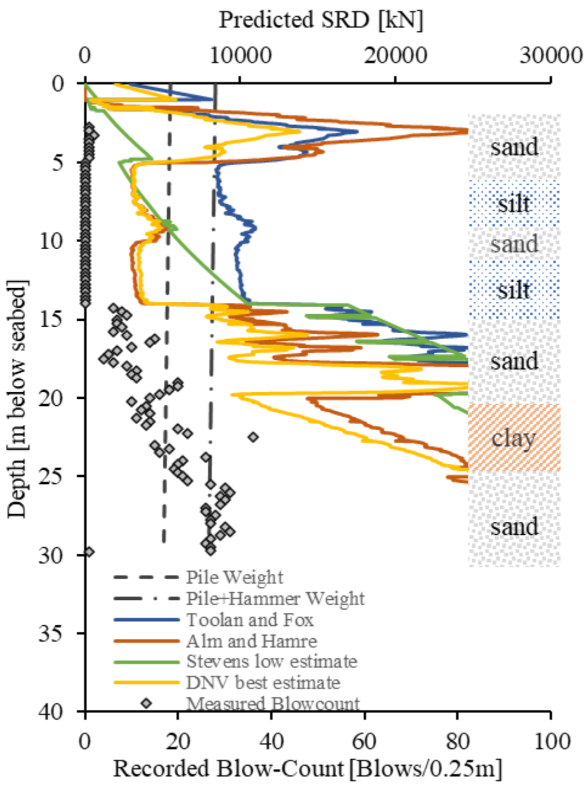

Fig. 1. SRD predictions – pile run case 1.

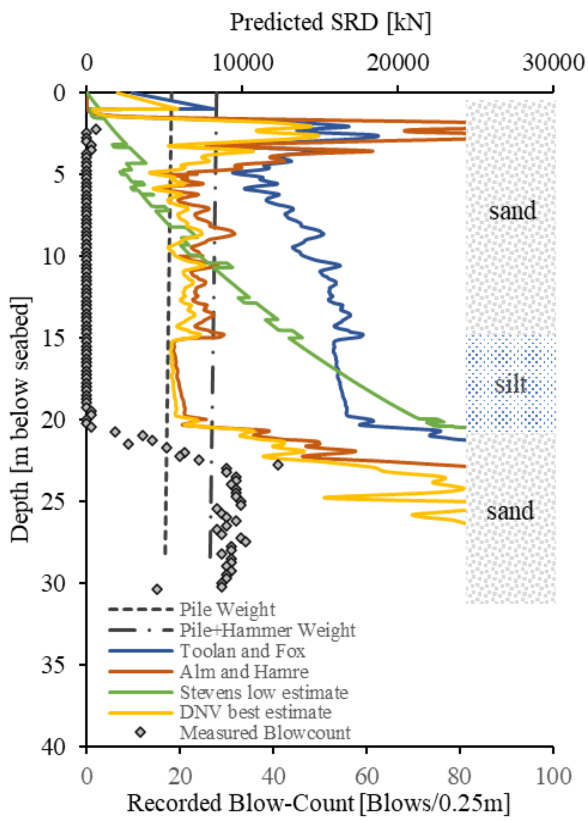

Fig. 2. SRD predictions – pile run case 2.

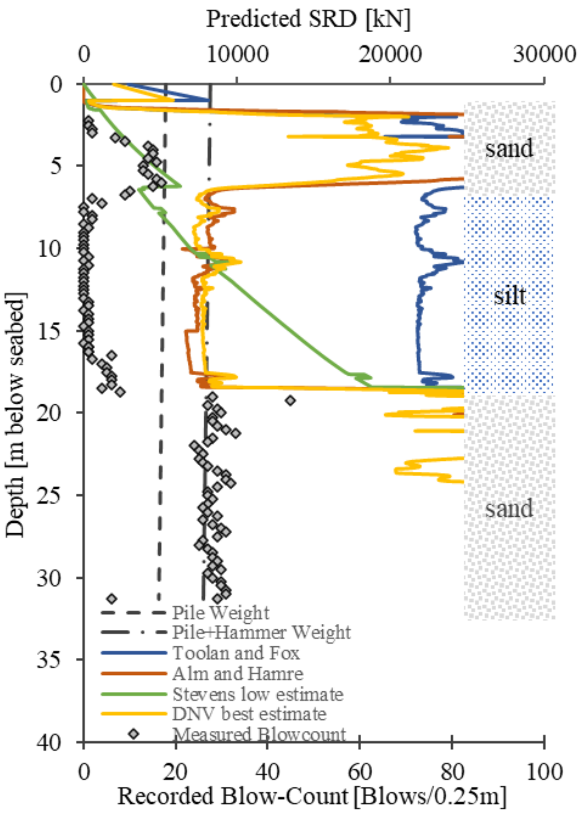

Fig. 3. SRD predictions – pile run case 3.

predicted SRD force should drop below the pile self weight force along the recorded pile-run zones. Conversly, should the predicted SRD force be larger than the pile weight force along a recorded pile run zone, the excess SRD force is measured (difference between the SRD force and pile and hammer weight force) and is compared to the pile weight force. It should be emphasised that the weight of the hammer was not included in the computations described above, as in modern offshore pile installation practice the hammer is typically detached from the pile when pile run initiates.

Fig. 4 provides an overview of how the predicted SRD force compares with the pile weight force according to each method. The DNV method produces overall the most accurate results, since the predicted SRD force is on average 24.7% larger than the pile weight force along the identified pile run zones. This means that while the method provides accurate estimates of the pile run locations, there are still zones along which the SRD was overpredicted. Toolan and Fox yields the least accurate results overall, as it overpredicts the SRD force by 167.8% on average along the pile run zones. The SRD computed with the Alm and Hamre method exceeds the pile weight force by 51.5% on average. Even though the method considers friction degradation, in some cases the SRD is significantly overpredicted. Furthermore, from Fig. 4, it might seem that Stevens method predicts the SRD with adequate accuracy in some cases. This is because the method yields very low SRD profiles at shallow depths that fall below the pile weight, however, this method is not suitable for predicting the extent of the pile runs when these reach greater depths.

5.2 Driveability Analysis

The driveability predictions computed with the Toolan and Fox, Steven's et al. and Alm and Hamre methodologies, as well as the modified Alm and Hamre model, are compared to the measured response at three wind turbine locations in Fig. 5, Fig. 6 & Fig. 7.

In general, all methods consistently overpredicted the driving resistance over the first approximately 7m of penetration. This is attributed to the input data to the analyses, and more specifically the CPT measurements. The measured cone tip resistance swiftly rises over the first metres of penetration, which leads to a high computed driving resistance, which is not observed in the pile driving records. Puech and Forey (2002) have described an upwards concave parabolic increase in cone tip resistance during the first metres of penetration in medium dense to very dense sands, similar to the ground

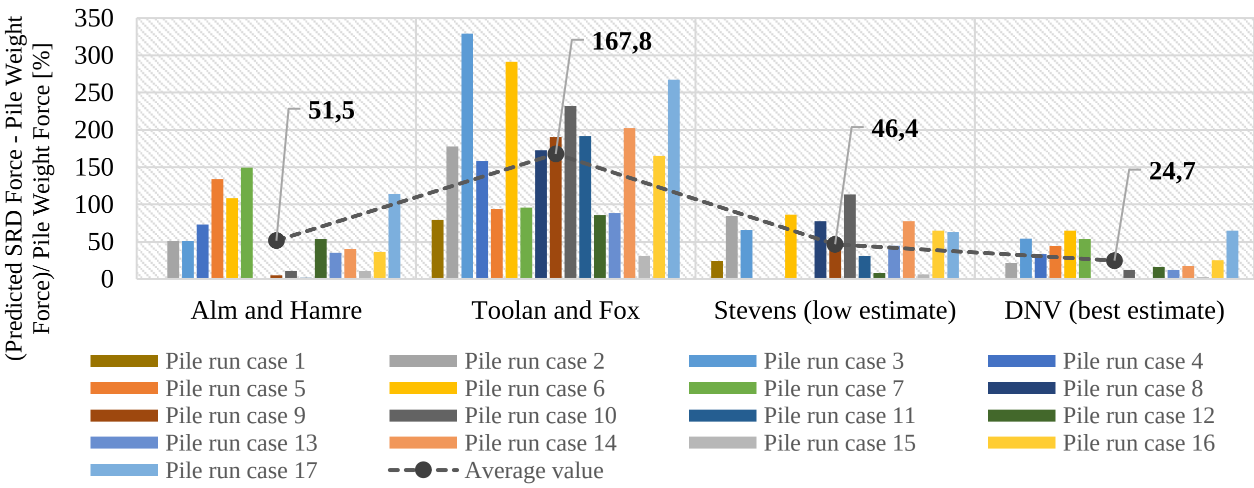

Fig. 4. Comparison of SRD prediction methods with respect to the average difference between the calculated SRD force and the pile weight force along recorded pile run zones.

conditions encountered at the examined windfarm site. They suggest that this rapid rise can be attributed to upward movement of the soil which surrounds the cone rods. On the other hand, the Toolan and Fox, Stevens et al. and Alm and Hamre (without modifications) methods typically underpredicted the driving resistance at greater depths.

The Alm and Hamre model produces the lowest blow-counts, underpredicting the measured response by approximately a factor of 2. Furthermore, the deviation between the Alm and Hamre output and the driving records became more significant with increasing depth. This suggests that the effect of the friction degradation concept, embedded in the Alm and Hamre method, whereby the friction resistance applied by the overlying layers degrades as the pile penetrates deeper into the ground, might be overestimated. On the other hand, the Alm and Hamre method seems to yield better estimates at locations where low blow counts were measured. Fig. 7 shows that this method provided predictions similar to the recordings for the weaker layer of silt which sits between 10m and 20m below seabed. Consequently, the method can be particularly useful for identifying weaker zones where pile run might occur.

The Toolan and Fox and Stevens methods usually produced similar blow-counts which typically lie higher than the Alm and Hamre predictions, as these methods do not consider a friction degradation mechanism. In many cases, the methods gave relatively accurate estimations of the pile driving response, even outperforming the Alm and Hamre approach, which is considered a more advanced method. However, both Toolan and Fox and Stevens et al. approach predicted blow-counts which did not reflect the low driving resistance along weaker silt and clay zones. As a result, low driveability zones, susceptible to pile-runs, could be overlooked, if pile driveability analyses do not consider a wider range of SRD prediction methodologies.

The modified Alm and Hamre method yields higher results compared to the original method, as the lower limit of the residual resistance has been raised to 50% from 20%, which was the value adopted by the original model. The measured response in most cases was accurately reflected by the modified Alm & Hamre, especially for sites characterised by predominantly Post-Glacial sand deposits (Fig. 5 & Fig. 6). However, the method seems to overpredict the driving resistance along low driveability zones (Fig. 7). Consequently, while the method gives accurate results in "normal" driving conditions, it is not suitable for predicting pile runs. It should be emphasized however that the accuracy of the predicted blow-counts along the soft zones could be affected by the over-predicted resistance in the overlying layers, especially when a reduced friction degradation effect is adopted. As it can be seen in Fig. 7, the higher predicted driving resistance in the upper sand layer, contributes to the predicted blow-count within the underlying softer silt zone, resulting in higher results.

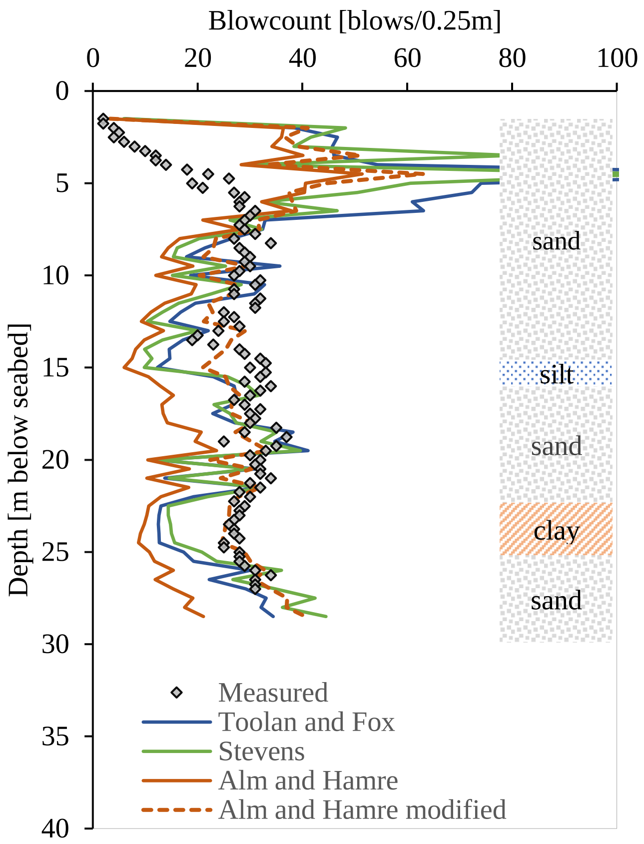

Fig. 5. Driveability predictions – indicative location 1.

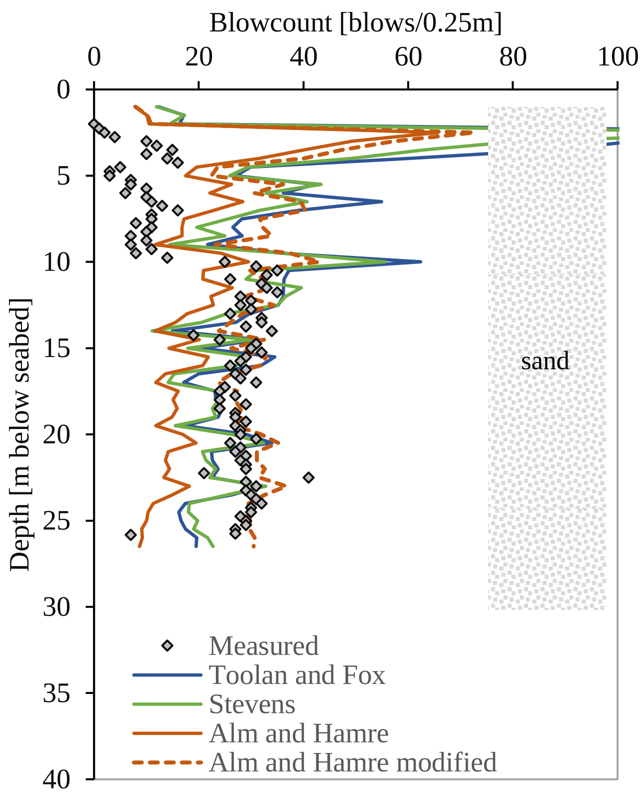

Fig. 6. Driveability predictions – indicative location 2.

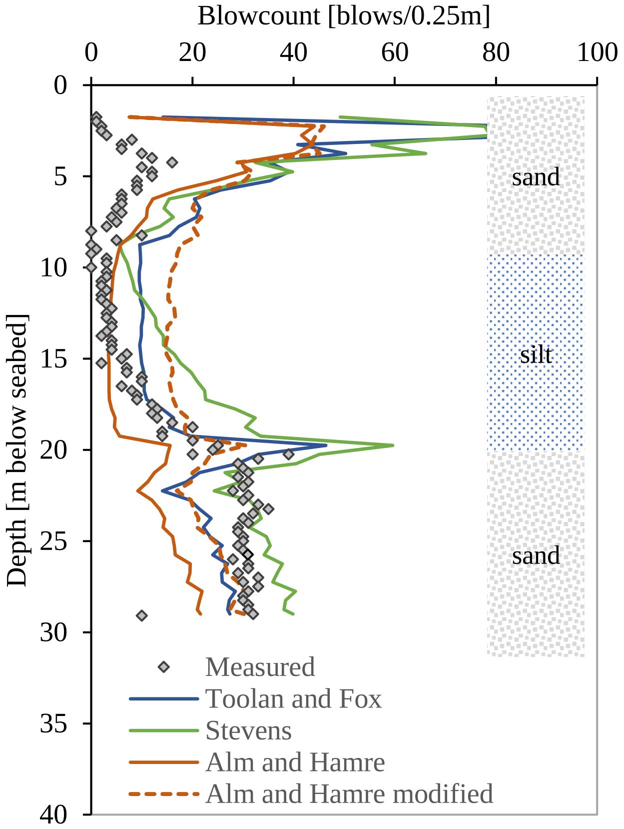

Fig. 7. Driveability predictions – indicative location 3.

In order to compare the methods examined above in a larger scale, driveability analyses were carried out in 10 WTG locations in total. Fig. 8 provides an overview of how all four methods performed in comparison to the measured blow-counts. The trends show the average absolute difference between the recorded and the predicted blows for each penetration increment (0.25m), providing an indicator of how accurately each method estimates the recorded blows. It should be noted that the upper 7m of penetration have been neglected from the calculation, since all methods yielded unrealistic results, attributed to very high CPT records. The modified Alm and Hamre model generally provided predictions closer to the recordings, with the average deviation between the recorded and predicted values lying in 7.9 blows per 0.25m of penetration. On the other hand, the least accurate results were produced by the original Alm and Hamre method (average difference 12.7 blows/0.25m), while the Toolan and Fox and Stevens predictions were both off by 10.1 blows per 0.25m on average.

6 CONCLUSIONS

Some of the most widely used SRD methods were assessed at a North Sea site which comprises Post-Glacial sands interlayered with silts and clays. The methods were first assessed regarding their accuracy in predicting pile-runs. Subsequently the original methods, as well as a modified version of one, were employed in driveability analyses and a comparison with the recorded response was undertaken.

The results indicated that the DNV approach could predict the pile run zones quite accurately in most cases, while the Alm and Hamre method produced similar, yet slightly overestimated results. On the other hand, the Toolan and Fox method was shown to significantly overpredict the SRD and hence to be unsuitable in identifying potential pile run zones. Stevens method was not suitable at accurately predicting pile run zones either, due to the method's formulas being dependent on confining pressures and not in-situ measurements.

The results from the driveability analyses showed however that when the Alm and Hamre method is employed within a driveability software, the blow-count was underpredicted, particularly at greater depths. It is tentatively concluded that the reasoning behind the underestimations is the method's friction degradation concept not reflecting the pile dimensions. Therefore, a modified version of the original Alm and Hamre method, with a reduced friction degradation effect was examined and found to yield more accurate results in most cases

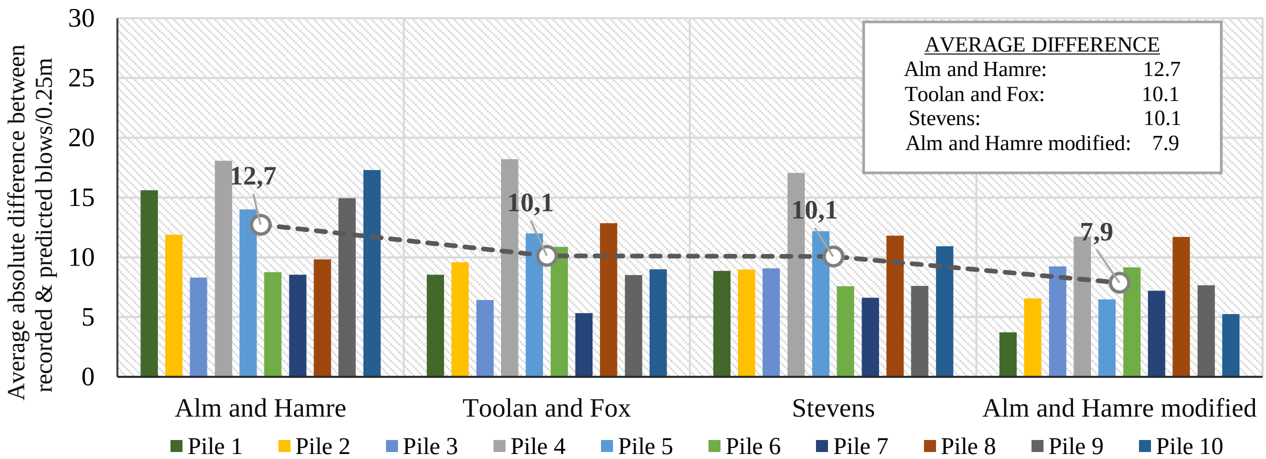

Fig. 8. Comparison of driving resistance prediction methods with respect to the average difference between measured and recorded blow-count.

analysed.

To conclude, the results of this study highlight the need of employing multiple methods when assessing driveability conditions, as some of the existing methods might yield unrealistic results for monopiles Modifications of existing methods or new methods based on driving records of monopiles are needed which should probably include a friction degradation term which is function of the pile diameter to wall thickness ratio.

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REFERENCES

1) Alm, T. & Hamre, L., 2001. Soil model for driveability predictions based on CPT measurements. In Proc. 15th Int. Conf. on Soil Mech & Geotech Engineering (pp. 1297-1302).

2) API, 2000. Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design. 21st ed. Washington, DC: American Petroleum Institute.

3) DNV, 1992. Det Norske Veritas, Foundations, Classification Notes 30.4.

4) Puech, A. & Foray, P., May 2002. Refined Model for Interpreting Shallow Penetration CPTs in Sands. Houston, Texas, Offshore Technology Conference.

5) Randolph, M., 2000. Pile-soil interaction for dynamic and static loading. In Proceedings of the 6th International Conference on Application of Stress Wave Theory to Piles. pp. 3-11.

6) Semple, R. & Gemeinhardt, J., 1981. Stress History Approach to Analysis of Soil Resistance to Pile Driving. Houston, Texas: Offshore Technology Conference.

7) Smith, E., 1960. Pile driving analysis by the wave equation. Journal of the Soil Mechanics & Foundations Division, ASCE, vol.86 (SM4), pp. 35-61.

8) Stevens, R., Wiltsie, E. & Turton, T., 1982. Evaluating drivability for hard clay, very dense sand, and rock. In Offshore Technology Conference. Offshore Technology Conference.

9) Toolan, F. & Fox, D., 1977. Geotechnical Planning of Piled Foundations. In: Proceedings of the Institution of Civil Engineers. Institution of Civil Engineers, pp. 221-244.