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Performance of different soil resistance models to assess the pile runs during offshore pile driving

Keshav Kashichenula, Kamaleshwar Sudhakaran, Soheib Maghsoodi
Heerema Marine Contractors, Leiden, The Netherlands

smaghsoodi@hmc-heerema.com (corresponding author)

ABSTRACT: Resistance loss of soil under the weight of pile or pile and hammer system can cause sudden downward movement of the pile or pile and hammer which is known as dropfall, or pile run. The pile run is a complex phenomenon which is a function of several parameters. The pile run can cause issues during the installation phase such as hammer load impact on the crane which can cause undesired vessel roll and consequently risk of re-hit on the monopile. To better understand the pile run risk, the static soil resistance based on current well-established methods are calculated and once the weight of pile or pile and hammer are more than the soil resistance the downward movement initiates. Due to the pile velocity the drained soil resistance can be become partially drained or undrained. This generates the soil resistance loss even in layers in which at static conditions the resistance is enough to bear the weight of pile or pile and hammer. In this paper reliability of several static soil resistance methods is examined against offshore pile run data. DNV and Alm and Hamre (2001) methods are evaluated against pile run data and the pros and cons of each method are described.

Keywords: Pile installation; intermediate soils; pile run; offshore; pile driving

1 INTRODUCTION

Offshore pile dropfall incidents present a critical challenge in marine construction, particularly in the renewable energy sectors. During offshore piling, piles can experience uncontrolled penetration, or "dropfall," when transitioning from hard to soft soil layers or encountering excessive hammering energy. These incidents pose significant risks, exerting high shock loads on cranes and pile-driving equipment, risking structural integrity, and often leading to operational delays. With the rapid expansion of offshore wind projects and the adoption of larger monopile designs that add substantial weight and inertia, the probability and impact of dropfall events have increased. Consequently, there is a growing need for advanced solutions to mitigate these risks and ensure safe, reliable monopile installation in varying seabed conditions.

The common pile run analysis consists of calculating the static soil resistance based on conventional static soil resistance to driving (SRD) or axial capacity methods then by adding the weight of pile and driving system, the energy equation solution can show the pile run start and end depth and the velocity of pile. The accuracy of these methods to predict the soil resistance is an influencing factor in this analysis. Different methods have been developed either based on empirical or CPT-based approach. Among them (API, 2000), (DNV, 1992), (Alm and Hamre, 2001), UWA-05 (Lehane et al., 2005), ICP (Jardine et al., 2005) and unified method (Lehane et al., 2020) can be mentioned. The DNV method, an empirical CPT-based approach based on DNV (1992), was initially developed for estimating the installation penetration resistance of a skirted foundation. Nevertheless, it has also found application in estimating the SWP of monopiles (Shonberg et al., 2017).

Kourelis et al., 2022 used different SRD/axial capacity methods to assess the accuracy of these models by comparing the predicted resistance profile with driving data of monopiles with 6.5 meter of diameter, installed in the Danish sector of the North Sea. The findings indicated that the DNV method generally provided accurate predictions of pile run zones, while the Alm and Hamre method produced similar results with a slight overestimation.

Thijssen and Roelen 2024 reviewed various soil resistance models to determine the most suitable approach for describing the mechanism of pile run. They noted that some models are best suited for static loading conditions related to long-term capacity, while others are designed to capture soil resistance under dynamic loading, such as the rapid accelerations encountered in driveability analyses.. Their experience with the Alm and Hamre model, across multiple projects, revealed significant mismatches in the initial stages of pile penetration, although the model's accuracy improved over the remainder of the penetration range. On the other hand based on existing driving data, Meissl et al., 2023 has mentioned that existing SRD methods are incapable of predicting properly the driving mechanism and soil response during pile installation. They mentioned the tendency of Alm and Hamre to overpredict the sand layer resistance at shallow depth.

To include the dynamic part of the pile run, Sun et al. (2022) proposed an analytical method to predict dropfalls during offshore pile installation by modelling pile-hammer interaction and soil resistance using API and CPT-based methods. Verified through case studies, they mentioned the model accurately predicted pile running depth but tends to overestimate velocity, likely due to partial drainage effects in silty layers.

In this paper, the effectiveness of three different methods—API, DNV, and Alm and Hamre (2001)—in predicting the static soil resistance for pile run analysis, is evaluated. Each of these methods provides a distinct approach to calculating soil resistance, and their accuracy is essential for reliable predictions in pile run scenarios. By comparing these SRD methods, the study aims to determine which approach most accurately reflects the soil resistance encountered during pile installation, helping to inform decisions on pile driveability and to minimize the risks of pile run.

2 METHOD

Two different static soil resistance methods in combination with an analytical model have been used to first calculate the soil resistance and then by comparing the pile or pile plus hammer weight with the soil resistance, provide the risky zone for pile run in addition with the pile run velocity. It is important to note that the industry has yet to define a standard velocity threshold for pile run. Once the pile reaches self-weight penetration, stabbing the hammer can initiate downward movement. The pile's velocity can help distinguish between a dropfall and a controlled pile sliding scenario.

2.1 Static soil resistance methods

A brief description of formulation of these methods is mentioned in the following Table.

Table 1. Summary of the equations in the SRD methods

Method	Cohesionless	Cohesive
Alm and Hamre 2001	Initial shaft friction: $f_{si}=(Ks\cdot\sigma'_{v0}\cdot\tan\delta)\cdot 0.5$ 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 (1992)	shaft friction: $f_s=k_f\cdot q_t$ end bearing: $f_s=k_p\cdot q_t$	

2.2 Analytical pile run model

The following energy equation has been used to obtain the velocity of the pile/hammer system during pile run (Sun et al., 2022):

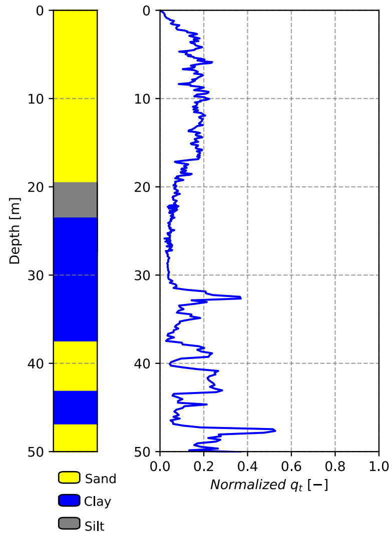
$$\frac{1}{2}(m_p+\chi m_h)(v_i^2-v_{i-1}^2) = [W_p + \xi W_h - F_b - (F_s + F_{end}) - F_d]\,_{\Delta Z_{tip,i}} \quad (1)$$

Where, m_p, W_p, m_h and W_h are the masses and weights of the pile and hammer respectively. v_i and v_{i-1} indicate the pile velocity at the start and end of the *i*th depth increment. F_b is the buoyant force exerted by the displaced soil, F_s is the shaft resistance, F_{end} is the end bearing resistance, F_d is the inertial drag force opposing the pile motion and χ denotes whether the hammer is on the pile (χ = 1) or separated (χ = 0) during pile run. ξ denotes the proportion of hammer weight applied during running. 20% of the hammer load was assumed to be applied after the pile reached a stable depth. If the additional 20% load caused a pile downward movement with positive velocity, then the weight was reduced to 10%. During the hammer stabbing if the soil resistance is close to the pile weight, incremental hammer weight adding is a way to avoid sudden drop of the pile. In this way, the pile goes down with the help of hammer weight. In the formulation, for incremental depths, kinetic energy caused by the mass and velocity is equated to the forces acting on the pile during pile driving. By including the energy transferred from the hammer or mass components, and resistance offered by the soil, pile velocity profile and depth progression can be modelled accurately. The equation is iterated for small depth increments ($\Delta Z_{tip,i}$) to obtain the velocity of the pile/hammer system for increasing penetration.

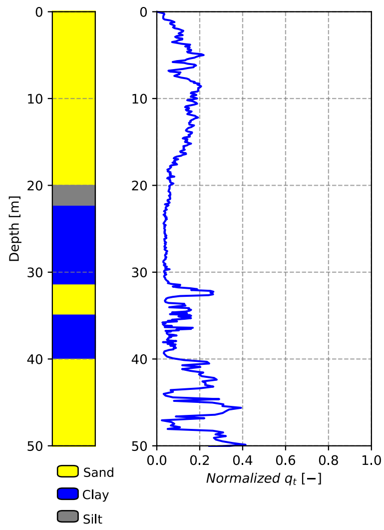
3 CASE STUDIES

3.1 Soil

The field involved in this study predominantly consists of layered soils consisting of loose to medium dense sands, low to medium strength clays and also transitional soils which are known for their susceptibility to resistance loss due to variable penetration velocity. The pile run analysis in this study uses data from 14 different locations (19 pile run cases), but due to space constraints, only two locations are discussed in detail in this paper. The normalized cone penetration test (CPT) profile of the two locations are referred to as location 1 and location 2 (see Figures 1a and 1b). These profiles, normalized against the maximum tip resistance for confidentiality reasons, show the soil type and normalized qt values. At location 1, the pile run began at a depth of 22 meters down to 36 meters, while at location 2, pile run initiation was observed at 21.75 meters, ending at 31.25 meters. Notably, in both profiles, the pile runs occurred within clayey sections of the soil, where lower soil resistance and potential for rapid, uncontrolled pile penetration are more common.



a)



b)

Figure 1. Normalized CPT and general soil profile on a) location 1 and b) location 2

Robertson, 2016 has mentioned the area represented by TC and TD is defined as "transitional soil," referring to soils that exhibit behaviour between that of ideal sand-like or clay-like soils. This category includes low-plasticity fine-grained soils, such as silt, which can sometimes respond in a partially drained manner during CPT testing (e.g., DeJong and Randolph., 2012). Such soils are also known as "intermediate soils". The soil in the pile run range has been classified based on the updated SBT_n chart of Robertson (2016) and it is shown in Figure 2. As can be seen around the pile run start depth (~22 m), the soil is transitional contractive/clay like contractive-sensitive.

At both locations, the piles have an outer diameter of 3.9 meters and a wall thickness ranging from 40 to 70 mm. Each pile weighs 312 metric tons (mT), and they are driven by a 613 mT hammer.

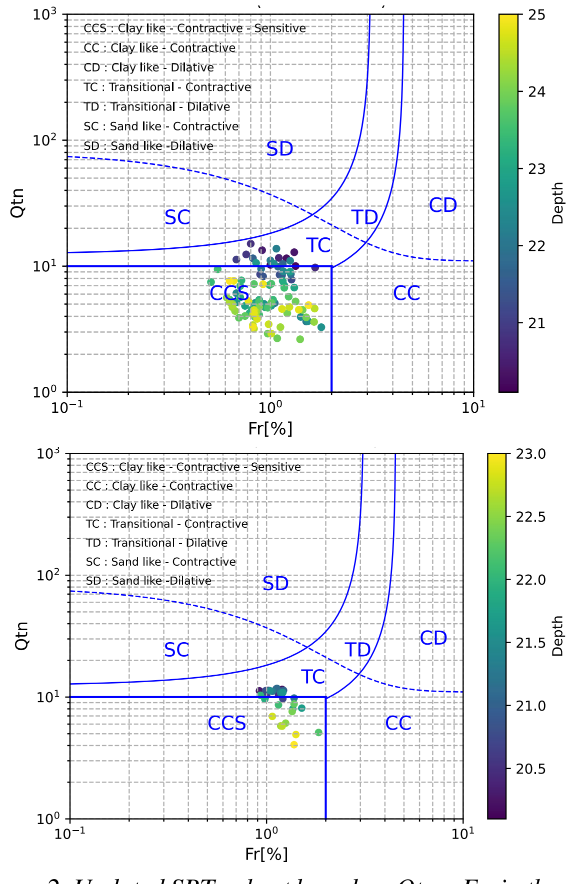


Figure 2. Updated SBTn chart based on Qtn – Fr in the pile run zone-location 1 and location 2

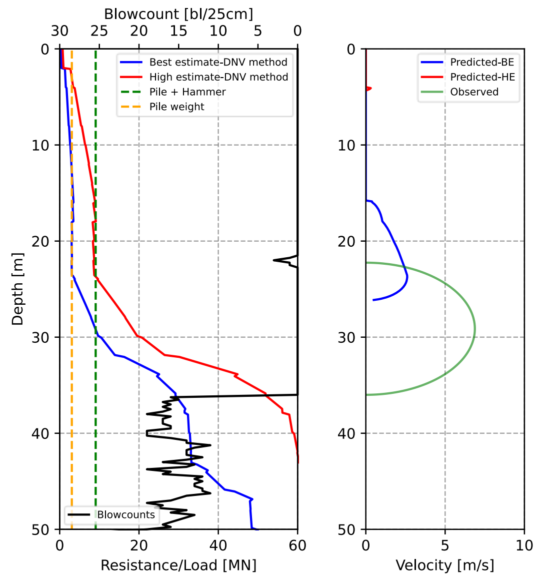
3.2 Pile

At both locations, the piles have an outer diameter of 3.9 meters and a wall thickness ranging from 40 to 70 mm. Pile length of all locations were around 70m. Each pile weighs 312 metric tons (mT), and they are driven by a 613 mT hammer.

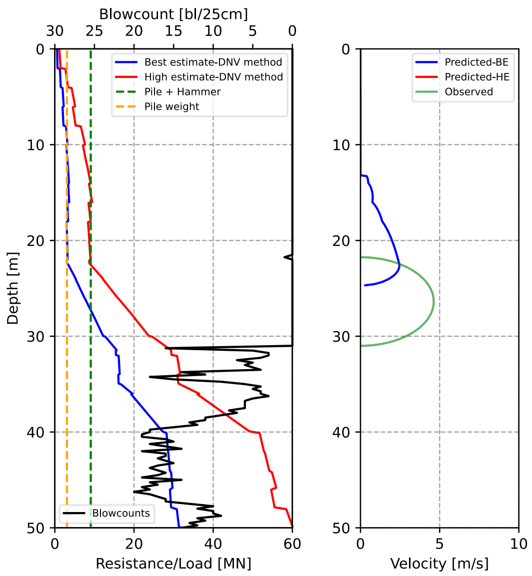
4 RESULTS AND DISCUSSION

4.1 DNV 1992

The best estimate of DNV approach for location 1, predicts the pile self-weight penetration before the start of pile driving. But due to the application of hammer weight (20% at the beginning) and the low resistance of the soil, a dropfall/sliding pile was predicted. Due to presence of clay and high shaft friction, the resistance increases quickly which leads to lower pile run end depth. The best estimate for location 2 shows similar trend as location 1. The DNV analysis can be seen in Figures 3a and 3b. For the high estimate, predictions for both locations 1 and 2 show a very small velocity spike which can be considered as a small pile sliding.



a)

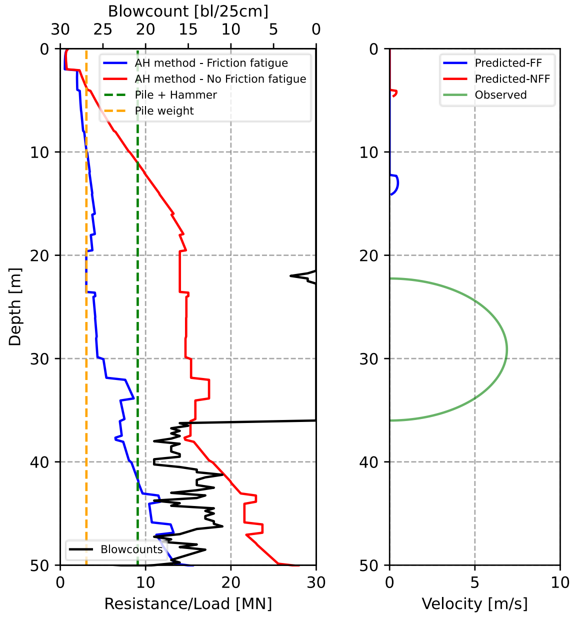


b)

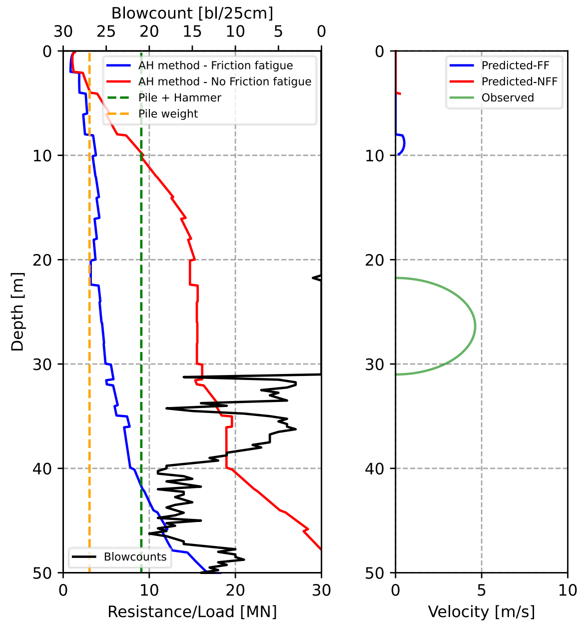
Figure 3. DNV method soil resistance for a) location 1 b) location 2

4.2 Alm and Hamre 2001

As seen in Figure 4, the Alm and Hamre prediction shows no significant pile downward movement. Figure 4 shows pile and pile and hammer self-weight penetration is not reflected correctly by the model. Capturing the pile's initial penetration under its own weight, is a critical factor in pile run analysis. Accurate prediction of self-weight penetration depth is essential because it sets the starting conditions for further pile movement.



a)



b)

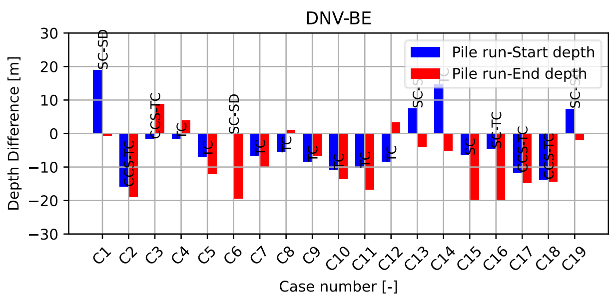
Figure 4. Alm and Hamre method soil resistance for a) location 1 b) location 2

5 DISCUSSION

Figure 5 shows the difference between predicted and observed pile run start and end depth, per pile run case for different soil resistance models. For DNV best estimate, 3 out 5 of the overpredicted pile run start depths (positive blue bars), the present soil profile is Sand. On the other hand, for the underpredicted start depths (negative blue bars), the transitional soil type is recurrent (the labels on the bars follow Robertson 2016 classification). For Alm and Hamre method, the same trend is observed. Out of 6 sandy profiles, 4 have been overpredicted. This trend is obvious for Alm and Hamre without friction fatigue method. Further investigation might be necessary to shed light on the reason behind this observation.

In Figure 6 the average of start and end depth per method is depicted. DNV best estimate has predicted the pile run start depth with -5.9 meters of underprediction. For the pile run start depth the method shows a very good agreement resulting in an average of -3.4 m. On the other hand for DNV High Estimate, pile run start and end depth have been under predicted by the model with an average of -17.3 m. Alm and Hamre with friction fatigue can replicate the start depth with some underprediction (-4.8 m). The end depth has been underpredicted by -13.0 m which makes the average -8.9 m. During offshore installation, underprediction might not cause serious consequences as it might imply earlier contingencies and awareness but overprediction consequences might be more serious.

It is important to note that no site-specific model tuning was performed in this study. To evaluate the performance of the models objectively and the analysis was conducted using the default method coefficients without any adjustments tailored to specific sites. From the interpretation of CPT design profiles to soil resistance calculations and pile run analysis, the models were applied "as-is," ensuring an unbiased assessment of their predictive capabilities.



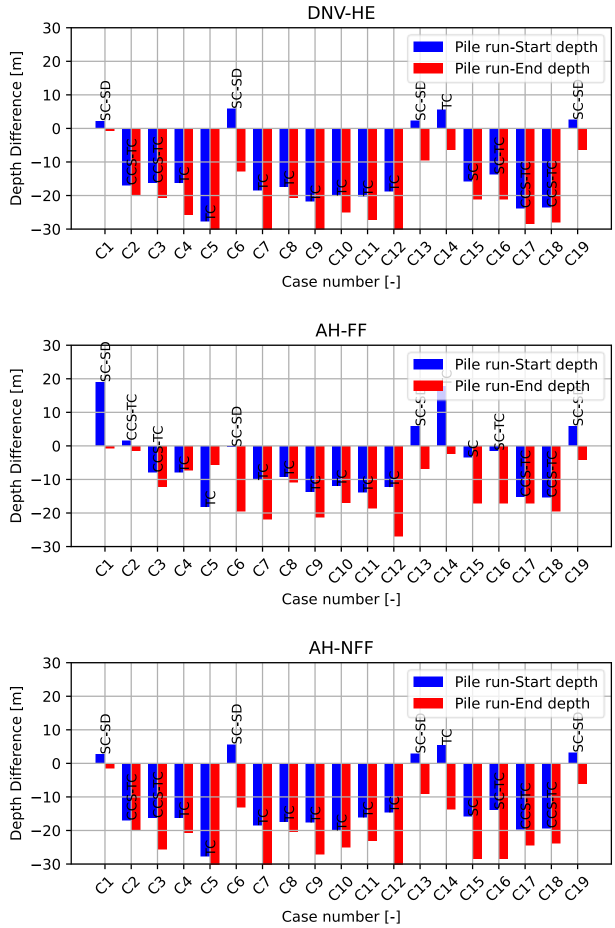


Figure 5. Method performance per pile run case: a) DNV-BE, b) DNV-HE, c)AH-FF, d)AH-NFF

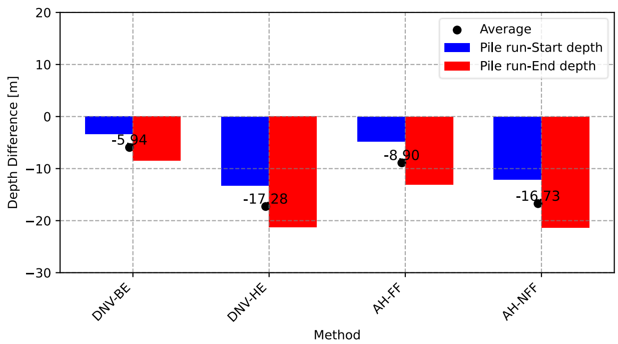


Figure 6. Different method performance in pile run start and end depth prediction

6 CONCLUSIONS

This study investigates the performance of two distinct soil resistance methods—DNV and Alm and Hamre—in assessing the pile run zone during offshore pile driving operations. Accurate prediction of this zone is essential for safe and efficient offshore pile installation. The evaluation was based on data collected from pile runs at 14 different offshore locations in the same field, encompassing a variety of soil conditions. 14 out 19 pile run cases happened in Transitional contractive/clayey like soil types indicating the importance of proper soil characterisation and classification. Updated Robertson Chart (Robertson 2016) was a useful classification to identify "risky" soils. Each method was assessed for its ability to predict both the starting and ending depths of pile runs/pile sliding. Although the models provided some predictions, the complex nature of pile run phenomena—being highly time- and rate-dependent—requires careful interpretation. It is essential to use physics-based methods or models with parameters that accurately capture the real phenomena for more reliable results.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data curation, Formal Analysis, Visualization, Writing- Reviewing and Editing. **Second Author**.: Methodology, Supervision, Writing-Reviewing and Editing . **Last Author**: Investigation, Conceptualization, Formal Analysis, Visualization, Supervision, Writing- Original draft, Writing-Reviewing and Editing.

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REFERENCES

Alm, T., Hamre, L. (2001). Soil model for pile driveability predictions based on CPT interpretations. In *International Conference on soil mechanics and geotechnical engineering* (pp. 1297-1302).

Thijssen, R., Roelen, S. (2024). Prediction of Pile Run During Pile Driving-Analytical Model and Field Observations. *In Offshore Technology Conference* (p. D021S026R004). OTC.

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

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

Robertson, P. K. (2016). Cone penetration test (CPT)-based soil behaviour type (SBT) classification system—an update. Canadian Geotechnical Journal, 53(12), 1910-1927.

Kourelis, I., Kontoe, S., Buckley, R., & Galbraith, A. (2022). An assessment of pile driveability analyses for monopile foundations. *11th International Stress Wave Conference, Rotterdam, The Netherlands.*

Sun, L., Shi, J., Zhang, Y., Feng, X., Tian, Y., & Wang, R. (2022). Analytical method for predicting pile running during driving. *Applied Ocean Research*, 125, 103234.

Jardine, R.J., Chow, F.C., Overy, R.F., Standing, J., 2005. ICP Design Methods for Driven Piles in Sands and Clays. London).

Lehane, B.M., Schneider, J.A., Xu, X., 2005. The UWA-05 method for prediction of axial capacity of driven piles in sand. *In: Proceedings of the International Symposium on Frontiers in Offshore Geomechanics (ISFOG).* Taylor & Francis, London, pp. 683‑689.

Meissl, S., Perikleous, G., & Stergiou, T. (2023, January). Development and interrogation of an extensive driveability database for offshore wind monopile foundations. *In Offshore Site Investigation Geotechnics 9th International Conference Proceeding* (Vol. 729, No. 735, pp. 729-735). Society for Underwater Technology.

Lehane, B., Liu, Z., Bittar, E., Nadim, F., Lacasse, S., Jardine, R. J., ... & Morgan, N. (2020). A new'unified'CPT-based axial pile capacity design method for driven piles in sand. In *4th International Symposium on Frontiers in Offshore Geotechnics* (pp. 463-477). American Society of Civil Engineers.