Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Discussion on SI strategy for the Foundation design and installation assessment for pre-investigated sites

Anthony Bouteiller
RWE Renewables Copenhagen

Pooyan Ghasemi*, Martin Böckler
RWE Renewables Hamburg

Mehdi Kadivar
RWE Renewables Boston

Lewis Cottee, Sam Litchfield, Andy Barwise

RWE Renewables UK

Pooyan.Ghasemi@RWE.com

ABSTRACT: Recent advancements in geotechnical design for the offshore wind industry primarily result from the adoption of 3D Finite Element Method (FEM) modelling. Key innovations include the PISA approach for monotonic loading, as well as advanced cyclic methods such as the Capacity Degradation Model (CDM) and Stiffness Degradation Model (SDM) by Achmus et al. (2003, 2009), and NGI's Cyclic Contour Diagram models (Anderson, 2015). However, these models have not been comprehensively tested across diverse soil conditions, leading to their cautious application and resulting in conservative designs by engineers. A significant consideration in 3D FEM-based design is the use of robust constitutive models and accurate parameter assignments. This has necessitated a re-evaluation of site investigation strategies, given that the new design methods are more sensitive to laboratory testing, thereby increasing geotechnical investigation costs. It remains uncertain whether still high costs particularly for in-situ testing (such as CPT), will lead to cost savings or de-risking during construction, including in foundation sizing and installation. This uncertainty, combined with higher expenses and extended timeframes required for obtaining detailed soil data, poses challenges for developers, particularly in the context of minimizing development costs. In this paper, the inherent uncertainty in geotechnical design methodology, irrespective of the availability of in-situ soil data, is compared with the uncertainty associated with predicted CPTs resulting from a high-quality inversion exercise. This comparison aims to provide a basis for optimizing site investigation campaigns for pre-investigated wind parks.

Keywords: Pre-investigated offshore wind parks. SI planning. Foundation design. Synthetic CPTs

1 INTRODUCTION

The offshore wind industry faces significant supply chain challenges and high uncertainty in project elements. Early-phase financial constraints often delay major investments in site investigations until projects are more mature. Shorter project timelines and larger-scale developments add to the complexity, with some countries conducting pre-investigations to mitigate risks. However, standards like BSH still require location-specific Cone Penetration Tests (CPTs), adding to development costs.

Delays in turbine selection and SI campaigns compress design timelines, requiring high cost certainty for earlier FIDs despite limited data. This often necessitates contingencies to address uncertainties, impacting project viability.

This paper highlights that while location-specific CPTs are crucial, other parameters such as cyclic testing, permeability, and damping also significantly influence foundation design. The uncertainties in these factors may be comparable to those arising from the absence of location-specific CPTs. Examples from North Sea sites illustrate these challenges, focusing on typical sand, silt, and clay formations.

2 REQUIRED PARAMETERS FOR ENGINEERING OF MONOPILE AND INSTALLATION ASSESSMENT

For an accurate design of offshore wind turbines, several key geotechnical parameters must be defined at each turbine location. These parameters serve as inputs for geotechnical models, which are essential for conducting the necessary assessments in wind turbine foundation design. Figure 1 provides an overview of the collected data (in orange), the key soil parameters (in grey), and the geotechnical models (in blue) involved in the design process.

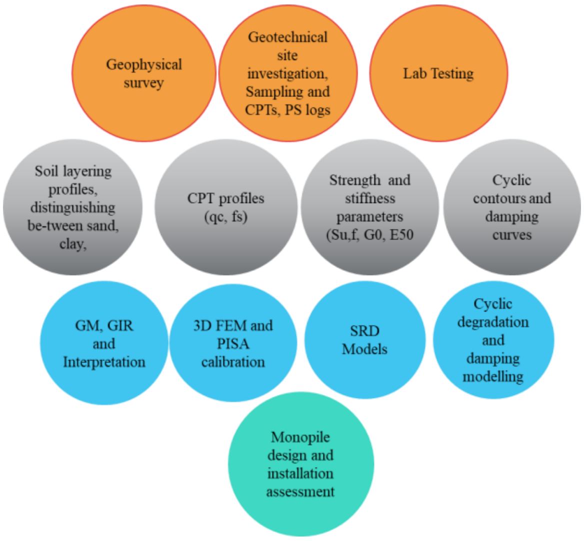

Figure 1, overview of the key elements of the geotechnical design of monopile

Since 2015, the industry has increasingly adopted advanced 3D Finite Element Method (FEM) analysis for monopile design, known as the PISA method. This approach requires more extensive laboratory testing to support the advanced constitutive models used in the analysis. With the increased size of wind turbines, especially in North Sea conditions, the geotechnical design driver for monopiles has shifted primarily to the serviceability limit state, which considers permanent deformations under cyclic loading. This state is highly sensitive to results from advanced cyclic testing and the interpretation of these results, as well as the methodologies used. This introduces inherent uncertainty into the latest design approaches, even when detailed site investigations and laboratory tests are available. Kanitz et al (2025) highlights the significant sensitivity of monopile design to variations in the shape of contour diagrams, even when derived from identical cyclic testing data.

3 UNCERTAINTY IN GEOTECHNICAL DESIGN OF MONOPILE

The uncertainty in geotechnical design can arise from various factors, including and not limited to: 1) Uncertainty in 3D FEM modelling and its sensitivity to laboratory testing, 2) Variability in methods for predicting pile driving resistance 3) influence of soil damping derived from laboratory testing, and 4) Uncertainty in cyclic degradation methods. In this paper, the focus is on the first two factors. The effect of other factors can be evaluated similarly in future studies. Here, the uncertainties of the geotechnical model are evaluated using statistical data from the literature and are compared against uncertainties associated with synthetic CPTs when location specific CPTs are unavailable. A case study involving two sites demonstrates the generation of synthetic CPT data using both traditional and new methodologies, highlighting significant differences in design and installation outcomes due to soil layering and CPT parameters (Qc and Fs).

3.1 Uncertainty in 3D FEM and constitutive modelling

Numerous studies have highlighted the sensitivity of 3D FEM-based monopile geotechnical design to various factors, including FEM solvers, mesh sizes, and modeling parameters. Fazlighiyasabadi et al. (2024) critique the reliability of the HS-Small constitutive model in industrial applications. They demonstrate the model's high dependency on sample preparation methods and its limitations in capturing realistic soil responses, affecting predictions for monopile behavior under various conditions.

Figure 2 shows distribution of the error of the 3D FEM models in the predictino of the lateral displacment of monopile under FLS and ULS load condition caused by uncertainity in the lab testing input and as well as constitutive model.

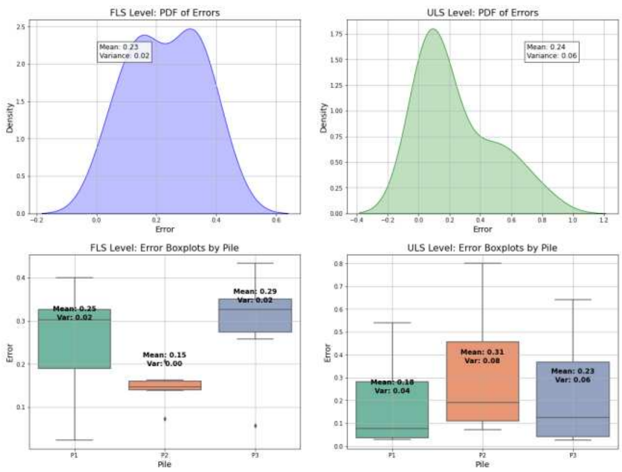

Figure 2. probability distribution function of the error in the 3D FEM modelling causing by the sample preparation and the constitutive model based on the data provided in Fazlighiyasabadi et al. left) FLS load level Right) ULS load level.

3.2 Uncertainty in Pile Drivability analysis methods

In the offshore wind industry, the common practice for conducting pile drivability analysis (PDA) relies on 1D wave propagation models, such as GRLWEAP. These models use soil resistance to driving (SRD) as a primary input from the soil side. Over the years, SRD has been developed based on back-calculation of a limited number of piles in specific soil conditions. Some notable examples of these models include Alm and Hamre (2001), Maynard (2018), Jones (2020), and, more recently, Perikleous (2023).

Many researchers have highlighted the inherent uncertainties of these models in predicting the actual behaviour of soil during driving, emphasizing the importance of exercising caution when applying them. To address this, Perikleous (2020) introduced a specialized statistical parameter called NRMSD (normalized Root Mean Squared Deviation) to evaluate the performance and accuracy of these models. Detailed calculations of NRMSD are provided in Perikleous (2023), where the model's performance is categorized accordingly:

- Good prediction: 0 <NRMSD<0.5
- Poor Prediction: 0.5 <NRMSD<1.0
- Very poor Prediction: 1.0 <NRMSD<10
- Non-acceptable predictions: NRMSD>10

The study by Perikleous (2023) shows that even for the newest SRD model developed (MonoDrive), at least 20% of the evaluated locations are classified as having poor or very poor prediction accuracy. The situation is even worse for the Alm and Hamre method, which is the most commonly used SRD model in the industry; more than 40% of locations fall into the category of poor or very poor prediction

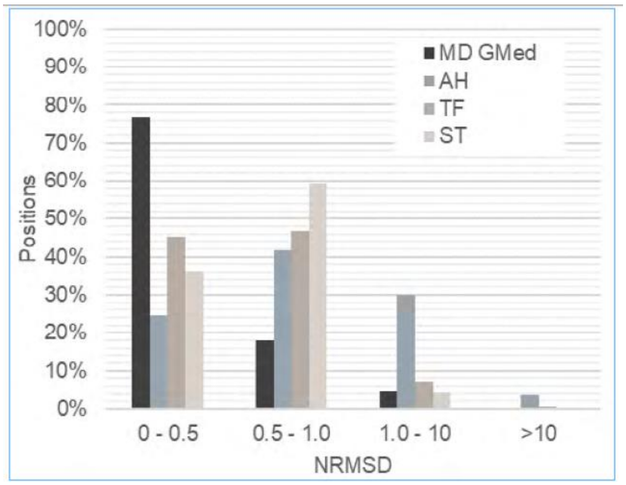

Figure 3, Comparison of NRMSD for different SRD model, MonoDrive (MD GMed). Alm and Hamre (AH), Toolan &Fox (TF) amd Strvens (ST) after Periklous 2023.

4 ACCURACY OF THE DESIGN BASED ON SYNTHETIC CPTS

Quantitative seismic interpretation, frequently referred to as synthetic CPT in offshore renewables, is an emerging tool in site characterisation. There are many possible approaches and the solution selected for each site needs to be tailored to the quality / quantity of data, project timeline, and how the end results will be used. The accuracy of this tool for design of monopile is discussed in this section for two case studies.

4.1 Case studies of HKW and TNW

The results of quantitative seismic interpretation are dependent on the input data, methodology of analysis, and the complexity of the site. Synthetic CPT was carried out by SAND geophysics and NGI for the TNW site (Input geophysical data from both HKW and TNW sites were 2D-Ultra Ultra High Resolution Seismic (2D-UUHRS) (Fugro, 2018, MMT, 2019). The quality of seismic imaging was high from both surveys although it is understood that additional data conditioning was undertaken prior to carrying out quantitative interpretation.

There are similarities in the methodology used for the quantitative interpretation at both sites (Fugro 2020 & NGI, 2022). Numerous methods were used at TNW. However, the most successful at both sites comprised an acoustic impedance inversion in addition to other seismic attributes and velocity analysis. An additional input for TNW was an inversion for seismic quality factor (inversely proportional to attenuation). There is a close relationship between Q-factor at grain size assisting with the differentiation of cohesive and granular sediments which makes this a useful input for geotechnical property prediction (Vardy et al., 2017). The methodology for both sites then used an artificial neural network (ANN) to convert the input the inverted products and attributes to predicted CPT parameters.

The approach for the acoustic impedance inversion differs between HKW and TNW. HKW utilised a deterministic model-based impedance inversion. However, TNW used a genetic inversion applied stochastically (Vardy et al., 2015). This approach is less sensitive to bias from the prior background model and captures the inherent uncertainty in the acoustic impedance inversion.

The complexity of the geological conditions and range of soil types, relative to the method being used, plays an important role in the reliability of ay quantitative interpretation. The geology of HKW is characterised by alternating sand and clay layers as well as numerous transitional silt layers. While all of these soil types are also present at TNW, the soil profile is more dominated by sand. Transitional soils and more heterogeneous soil properties represent a challenge for quantitative seismic interpretation, where the relationship between acoustic impedance (and other derived inverted or derived attributes) is more complex and non-unique.

It should be noted that applicability of quantitative interpretation should be evaluated on a site by site basis. Accuracy of the prediction in the examples shown generally became less reliable with increasing depth, largely due to the decrease in geotechnical data availability and decrease in the quality of seismic imaging. Engineering analysis using synthetic CPT on sites with longer expected pile lengths may be less reliable, depending on the site investigations carried out. Furthermore, any engineering design from synthetic CPT in regions with other geohazards (e.g. seismicity) or complex soils / rocks may be more sensitive to such inaccuracies. Finally, to achieve reliable results from quantitative interpretation requires exceptional seismic data quality and sufficient geotechnical data for the methodology being considered. Both the example projects had a significant number of geotechnical data to input into the analysis.

4.2 Derivation and comparison of design soil profile

To establish geotechnical design parameters for foundation engineering, soil profiles were developed using both in-situ Cone Penetration Test (CPT) results and predicted CPT data derived from advanced ground modelling techniques. The interpreted and predicted profiles were constructed based on certified project methodologies, ensuring adherence to approved procedures for layering and unit definitions.

Key geotechnical parameters—including undrained shear strength, friction angle, small-strain shear modulus, and relative density were calculated using project-approved formulas, consistently applied across both methods. To demonstrate the effectiveness of the approach, design soil profiles were derived and compared using examples from two distinct projects. Two examples of the predictions for projects HKW and TNW are shown in Figures 3 and 4, respectively. These represent cases known for poor predictions of the CPT profile in the inversion studies conducted by Fugro (2020) and NGI (2022). The number of CPTs at the top of the figures corresponds to the same naming used in the mentioned references.

4.3 Accuracy of the pile embedded length.

The PISA rule-based methodology was employed for the analysis, utilizing formulations specific to Dunkirk sand (Burd et al.) and Cowden clay (Byrne et al) for both interpreted and predicted profiles. The evaluation focused on comparing the embedment length by parking the uncertainty of the design methodology aside and just , to focus on the uncertainty associated with using synthetic CPTs. The pile embedded length is calculated under a typical North Sea load condition for 15 MW turbine.

The cyclic degradation factors of API is considered for this calculation. The design driver of the pile length was set the permanent rotation equal to 0.25 degree calculated based on a push over plastic loading followed by an elastic unloading adopting initial stiffness of soil springs.

As mentioned, locations being shown in this study are the one which provides less accurate predictions of the qc and fs using synthetic data in the report of Fugro (2020) and NGI (2022).

The comparison of in-situ and predicted profiles revealed variations in monopile embedment lengths, with differences of up to 2 meters, as shown in the *Figure 6*. For HKW, the design based on in-situ data required a shorter pile length (approximately 1 meter) compared to the predicted profile, despite using the same monopile diameter and applied load. This suggests that the predicted profiles for HKW were less conservative than the in-situ data, which may impact the overall design and foundation safety margins.

For TNW, the predicted profiles were generally more conservative, with longer embedment lengths compared to the in-situ data. and the designs are closer to each other with differences of up to 1m. Similar to the accuracy index defined for 3D FEM modelling and PISA calibration, the accuracy index can also be defined as the ratio of the difference (absolute) in pile length to the pile length based on actual CPT data (η). For the HKW site, the parameter η has a mean (μ) of 0.034 and a variance (σ^2) of 0.0009. For the TNW site, the mean (μ) of η is 0.0278, with a σ^2 = 0.0004. When considering both sites collectively, the mean (μ) of η is 0.0313, and σ^2 is 0.0006.

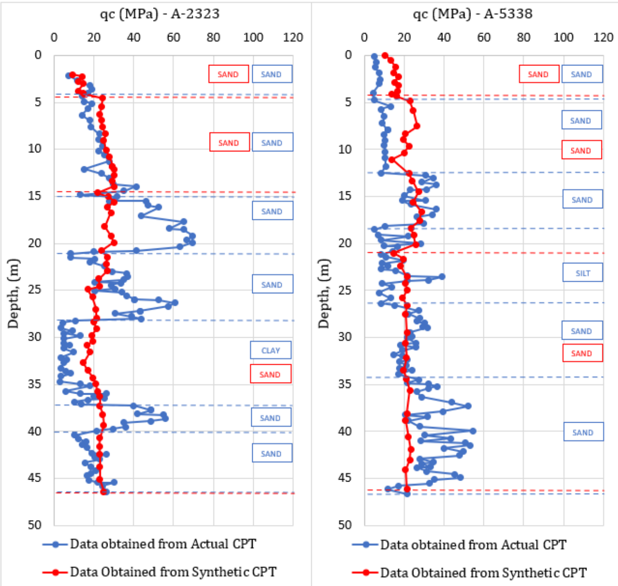

Figure 4, Cone resistance profiles for HKW, showing in-situ test results (blue) and predicted values (red).example of poor prediction.

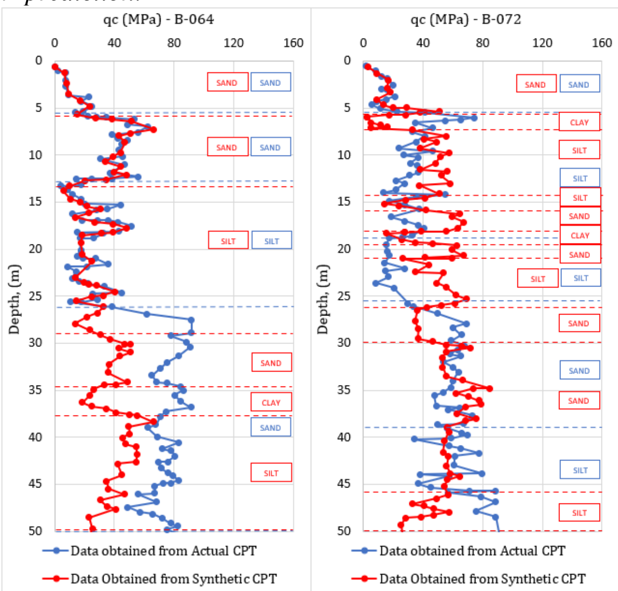

Figure 5 Cone resistance profiles for TNW, showing in-situ test results (blue) and predicted values (red). Example of week prediction.

A comparison of these statistics with the μ and σ^2 of the error associated with the uncertainty of the 3D FEM model and the PISA model indicates that the accuracy of the predicted CPTs falls within the allowable error range of both the 3D FEM and PISA models.

4.4 Accuracy of the pile embedded length.

All of the piles used for the analysis of pile embedded length were also used for evaluating the accuracy of the PDA. An example is provided for HKW (

Figure 8-a) and TNW (

Figure 8-b). A comparison of monopile drivability using actual and synthetic CPT data highlights key differences in blow counts, total capacity, and stress profiles, all of which are crucial for offshore wind foundation design. Each project used the same hammer specifications (S-4000 hammer with 2.02m stroke) and the Alm & Hamre (2001) method to determine soil resistance.

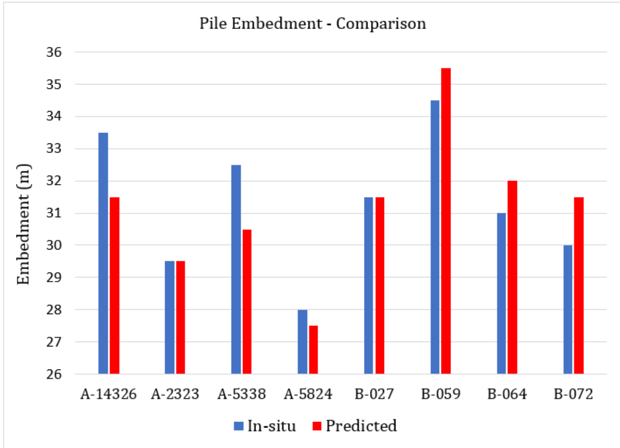

Figure 6. Comparison of pile embedment between in-situ data and predicted values for the analysed positions in Projects A (HKW) and B (TNW).

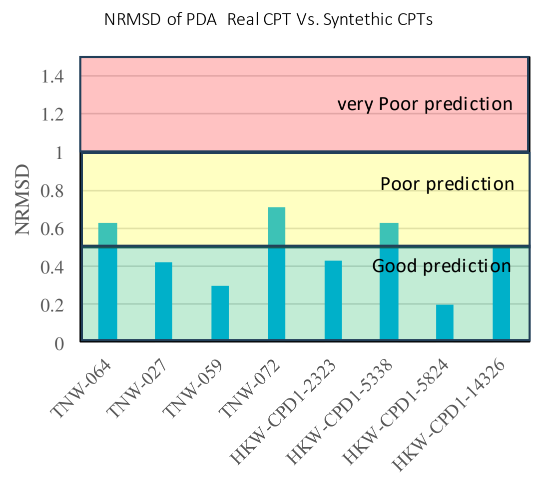

Figure 7 overview of the calculated NRMSD for specific locations, identified as having poor CPT predictions.

Similar to the NRMSD definition by Perikleous (2023), the same indicator is used here to evaluate the performance of predicted CPT profiles in the context of PDA. The primary distinction is that, in this study, the error is calculated as the difference between the blow count obtained from the actual CPT profile and the blow count derived from the predicted CPTs, while other parameters (e.g., hammer energy and pile dimensions) remain unchanged.An overview of the calculated NRMSD for specific locations, identified as having poor CPT predictions, is shown in Figure 7. Notably, although the CPT predictions may initially seem imperfect (e.g., as seen in Figure 4 and 5), the majority of locations are categorized as having good predictions, as defined by Perikleous (2023). Approximately 38% of the evaluated locations fall under the poor prediction category, which aligns with the percentage observed in the Alm and Hamre model for this category, as depicted in Figure 3.

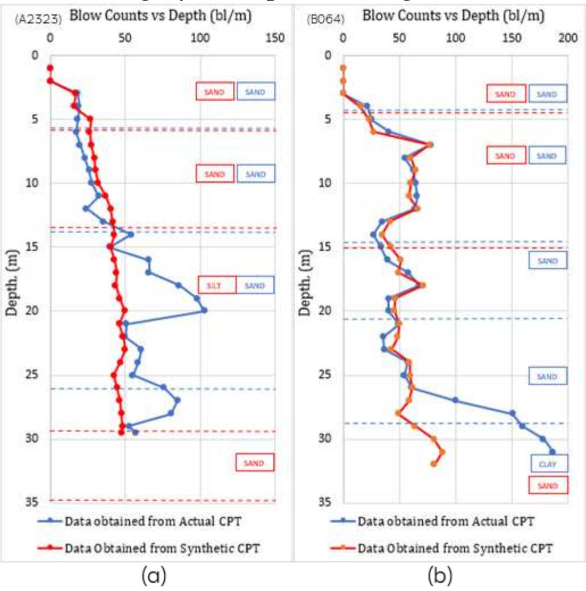

Figure 8 Blow count calculated using the predicted CPTs vs actual CPT profiles – example of HKW (a) and TNW (b)

5 DISCUSSION AND CONCLUSION

In this study, the expected error in two key aspects of the geotechnical design of monopiles, namely lateral capacity and pile drivability assessment, considering various sources of uncertainty in the methods and inputs, is discussed. The study utilized two case studies from the Dutch North Sea, where site investigation data are available from the Dutch government website (RVO).

It has been demonstrated that the expected error in the main outcomes of the lateral capacity check using synthetic CPTs can be comparable to the inherent uncertainty and inaccuracies of the methodology, which may be caused by factors such as the selection of constitutive models or sample preparation in laboratory testing activities. This observation is particularly valid for the TNW case study, where an acoustic impedance and Q-factor inversion, as well as other derived seismic attributes, were followed by an ANN to predict CPT. Similar conclusions can also be drawn for pile drivability analysis. The results indicate that the inaccuracy and variations in predicted blow counts between real and synthetic CPTs are within the same range as the inaccuracies of the SRD models used in the industry for PDA analysis.

In conclusion, the geotechnical design of monopiles inherently involves uncertainty, especially when advanced 3D FEM modelling methods are used. It is important to note that the findings of this study are based solely on two case studies from Dutch North Sea conditions, particularly at the TNW site, where synthetic CPTs were developed using a substantial quantity of high-quality geophysical and geotechnical data, and where the ground conditions are well-characterized. Therefore, the conclusions of this study cannot be generalized to other sites without further investigation.

AUTHOR CONTRIBUTION STATEMENT

Anthony Bouteiller: Calculations and data management. **Pooyan Ghasemi**: Conceptualizing, writing, calculations. **Martin Böckler**, QA and review Mehdi Kadivar: Calculations, **Lewis Cottee**, **Sam Litchfield, Andy Barwise**: Review and consultation

REFERENCES

Achmus, M., Kuo, Y. S., Abdel-Rahman, K., Tseng, Y. H., & Pang, I. (2020). Capacity degradation method for piles under cyclic axial loads. *Computers and Geotechnics*, *128*, 103838.

Byrne, B. W., Burd, H. J., Zdravković, L., McAdam, R. A., Taborda, D. M., Houlsby, G. T., ... & Gavin, K. G. (2019). PISA: new design methods for offshore wind turbine monopiles. *Revue Française de Géotechnique*, (158), 3.

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.

Fazlighiyasabadi, S., Goodarzi, M., Fetrati, M., Kreiter, S., Galavi, V., Ibsen, L. B., ... & Mörz, T. (2024). Practical considerations for numerical simulation of large-diameter monopiles for offshore wind turbines in overconsolidated sand: A case study of the VIBRO project in Cuxhaven, Germany. *Ocean Engineering*, *313*, 119365.

M. Kanitz , J. Dührkop, Impact of cyclic contour diagram definition on monopile design for offshore wind turbines. *Isfog 2025.*
NGI2022 TNW, RVOwebsite,https://offshorewind.rvo.nl
Fugro 2022, HKW RVOwebsite,https://offshorewind.rvo.nlb3