

The importance of data management to drive innovation in offshore geotechnics

Oda Mohus, Kristin Paulsen, Ryan Stelzer, Truls Martens, Thomas Langford
Norwegian Geotechnical Institute, Norway, oda.mohus@ngi.no

ABSTRACT: Amid the energy transition, offshore geotechnics is at a pivotal point where the development rate of the industry needs to remain high to meet the goals of The Paris Agreement. These forecasts require us to balance the availability of vessels, equipment and laboratories for geodata acquisition against more disruptive emerging technologies and smarter data utilization that can significantly reduce site characterization time. Central to this is geodata management. Effective geodata management from a project's inception ensures informed and efficient decision-making throughout the project by means of enhanced geodata collection, processing and interpretation and geodata integration into evolving ground models that account for design parameters and uncertainties. The use of APIs (Application Program Interfaces) allows for dynamic and seamless communication between digital products that foster digital innovation across stakeholders. Effective geodata management unlocks significant cost reductions, a reduced carbon footprint, and faster project execution. This is achieved through well-scoped site investigations based on desk studies and dynamically updated ground models throughout the project lifecycle. These practices permit optimized field and laboratory testing programs as well as earlier and more reliable design workflows. Lab programs and target depths for sampling boreholes or *in-situ* testing can be updated as new test results become available, often based on variations within interpreted units and anchored in data-driven design screening. This paper gives an overview of these technologies and highlights the relevance to the practicing geotechnical engineer.

KEYWORDS: Offshore site investigation, data management, data collection, application program interfaces, streamlined workflows.

1 INTRODUCTION

The urgency of climate change mitigation, as outlined in the Paris Agreement, has placed unprecedented pressure on the offshore wind industry. For instance, according to the European Environment Agency (EEA), the EU offshore wind capacity must grow from approximately 19 GW in 2023 to 111 GW by 2030, and 317 GW by 2050 (EEA, 2024). Increasing project scale, reducing project timelines, deeper waters and more challenging seabed conditions put greater pressure on the geotechnical engineers. Reliable and efficient site characterization is essential for safe and cost-effective foundation design for offshore wind, while project timelines and cost expectations are decreasing. To meet the requirements of efficiency and reliability in the offshore site investigation phase, it is essential to have good data management routines (European Commission, 2022).

Establishing a suitable geotechnical database for foundation design is a continuous challenge. The industry is facing challenges like limited availability of site investigation vessels, which necessitates greater optimization of site investigations. Improved data management can unlock the possibility of establishing a dynamic database which is continuously updated with the most recent data. This supports improved planning of site investigations and allows for real-time updates of the site investigation strategy during a campaign. This way, it is possible to maintain necessary data coverage and data quality, whilst potentially reducing the overall scope and duration of the offshore site investigation.

With well-structured geodata flow, it naturally follows that standardized outputs and data formats are also established. This is essential for deriving streamlined workflows where outputs from one phase become the inputs for subsequent phases (e.g., shear strength profile and design loads are fed into software for sizing foundations).

2 SIMPLIFIED GROUND MODEL

Dimmock et al. (2025) defines a ground model as a 3D representation of the ground, including surface and subsurface, and processes that may change the ground, over a development area or area of interest. A ground model is based on geological understanding integrated with geological, geophysical and geotechnical data. Development of a robust ground model is crucial for large offshore wind projects due to the size and

complexity of the sites. It is also important to integrate geological understanding from the ground model into geotechnical interpretation. To do so, effective geodata management is key.

3 DATA MANAGEMENT

Effective data management practices can reduce risks and enable significant cost reductions and accelerated execution timelines through optimized resource utilization. Data-driven decisions in real-time make it possible to maximize the value extracted from limited vessel time and laboratory capacity, whether it is reducing borehole depths, modifying field investigation scope, or adjusting laboratory test programs based on continuously updated ground models and preliminary designs.

3.1 Database and Access Control

A robust data platform forms the foundation of effective geodata management. All ground investigation data from the field and lab must be structured and stored in secure, reliable databases with backup and recovery systems. As critical energy infrastructure, data related to offshore wind installations require robust cybersecurity measures to protect against data breaches, ransomware, and other cyber threats.

Furthermore, having a data platform that serves as the “single source of truth” is crucial as offshore wind projects scale to multi-gigawatt developments involving numerous stakeholders. Access control mechanisms enable secure, role-based data sharing while maintaining data integrity and confidentiality across collaborating organizations.

3.2 Application Program Interfaces (APIs)

Modern offshore wind developments require efficient interpretation of soil parameters and streamlined design for hundreds of foundation locations. The technical backbone supporting this workflow relies on Application Program Interfaces (APIs) that facilitate efficient data communication between different software and analytical tools. APIs enable real-time integration of the data platform with geotechnical analysis software and foundation design tools, facilitating streamlined workflows that process data efficiently using open data formats. This integration eliminates manual data transfer, minimizes transcription errors, and accelerates the design process in a scalable and robust fashion. In addition, API-

based software gives flexibility to the user, by allowing for interaction with the data on several steps within the workflow. By using API calls, users can externalize specific parts of the workflow to use project-specific calculation methods where necessary. Where no non-standardized approaches are needed, the integrated methods in the software can be used for the entire workflow.

3.3 Version Control – Phases and Revisions

As the ground model and foundation design are continuously updated, version control of revisions in each phase of the project is key to ensure that results are traceable and reproducible. Version control ensures that all project participants refer to current, validated information while maintaining historical records, enabling iterative updates to ground models that support evolving designs throughout the project lifecycle.

3.4 User interface

In offshore wind development, where decisions impact project economics and resource utilization, user-friendly interfaces are not merely convenient, but a necessity. The ability to quickly upload raw data files from vessel owners and maintain clear version tracking enables teams to begin preliminary analysis immediately. This early access to data

allows for real-time optimization of vessel operations while maintaining the flexibility to update analyses as refined data becomes available.

Modern frontend technologies have transformed how engineers interact with complex datasets. Interactive map interfaces enable engineers to explore the data and provide clear visual connections between subsurface conditions and proposed asset locations. These tools allow engineers to navigate seamlessly between data visualization and real-world context, facilitating faster interpretation and more confident decision-making.

Interactive plotting capabilities and data grouping functionality empowers teams to conduct streamlined analysis for multiple locations at the same time. Figure 1 shows data from cone penetration testing (CPT) within a Graphical User Interface (GUI) that allows for interactive assignment of units and unit boundary depths. When combined with intuitive navigation and responsive design, these features enable rapid identification of risks and accurate preliminary foundation design. This enhanced analytical capability directly translates to more timely decisions regarding adjustments to the field test program and laboratory test prioritization, which ultimately leads to better utilization of resources while maintaining the highest standards for accuracy of the analysis.

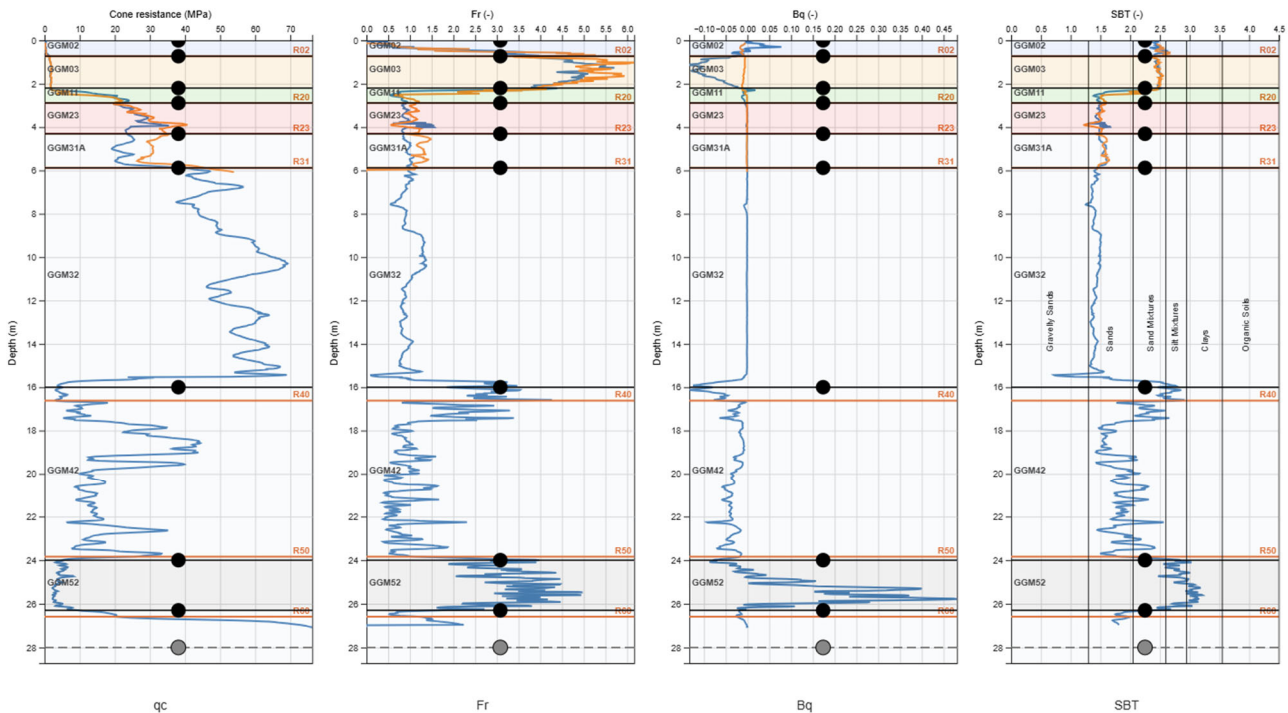


Figure 3-1 CPT data plot with interactive unit assignment and handles for adjusting unit boundary depths. New units are easily added by simply clicking in the plot window, while the assigned unit can be changed by right clicking the black dots. Geophysical horizons are shown as orange horizontal lines. Example data from TNW (RVO, n.d., Sauvin, 2024).

4 GROUPING OF GEOTECHNICAL DATA

4.1 Location groups

After a sampling borehole or *in-situ* test (e.g., CPT, plate dilatometer, seismic shear wave velocity, pore pressure dissipation, etc.) has been completed, the location in the ground is given a unique ID and individual result file with geospatial coordinates. It is typically useful to interpret *in-situ* tests and/or borehole locations in close proximity as one single location.

This allows for combining information to create a more holistic interpretation (e.g., via calibration of *in-situ* testing relationships to laboratory test results). Therefore, it is important to have a location grouping system, which is especially applicable to locations with bumpovers. A bumpover location is identified as an *in-situ* test or borehole location offset a short distance from a parent location, performed due to early termination of the original borehole (e.g., refusal on a boulder) or to fill gaps in the original dataset (e.g., through use of different drilling, sampling or testing methods).

In this paper, we will refer to a collection of individual *in-situ* tests and/or boreholes, performed close enough to each other to have the same unitization, as a location group. The distance between two individual locations depends on the spatial heterogeneity of the seabed. For example, two CPT locations only a few meters apart, could be considered two different location groups if the one CPT penetrates through a tunnel valley with clay infills and the other does not. Conversely, two CPT locations further apart could be considered one location group if the seabed is flat and laterally homogenous.

An individual location can only belong to one location group. Two locations belonging to the same location group have, by definition, the same unitization.

4.2 Group purposes

For some projects, it is beneficial to further group different locations together. To do so a second layer of grouping is introduced, referred to as group purpose. A group purpose can consist of several location groups, but unlike for the location group level, a location group can belong to multiple group purposes. Each group purpose has its own unitization, which either can be a copy of one of the location groups or a unitization that is representative of all location groups within the group purpose.

An example of a group purpose can be a three-legged jacket structure footprint, with one location group in the center of the location and one location group per leg (Figure 2). However, for an overall assessment of the jacket footprint, all four location groups can be plotted and analyzed together in the same group purpose. Another useful application of this second layer of location grouping is when dealing with zonation, where several WTG locations will be considered together with one representative unitization and set of design lines. Zonation is more common for sites with less lateral variation in stratigraphy.

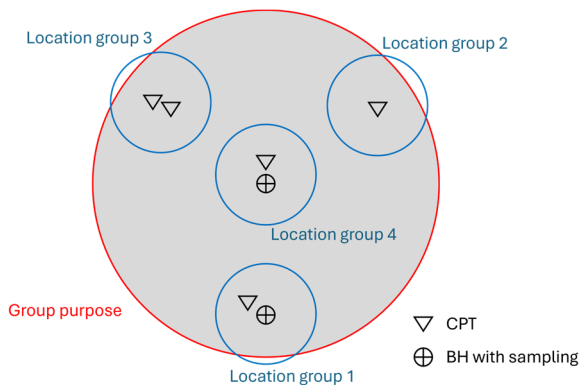


Figure 4-1 Plan view of group purpose vs. location group.

4.3 Soil and rock units

As previously discussed, spatial grouping of data (e.g., based on lateral separation) is an important part of data management and interpretation. Of equal importance is grouping of data into soil and rock units across the site, based on the geological and geotechnical understanding.

Due to variations in the geological depositional environment, the soil and rock units exhibit different engineering properties and therefore require different types of characterization tests (e.g., point-load testing versus triaxial shear testing). Soil units are further divided into coarse and fine grained material, while rock can have different degrees of weathering. Various geological processes can make it such that

a soil behaves similarly to a weak rock (e.g., cemented sands) or a rock behaves similarly to a high strength soil (e.g., weathered mudstone). It is important to distinguish between the two types to ensure useful and representative design parameters are determined for analysis. These divisions can be further refined with additional testing information (e.g., grain size distribution to distinguish between clean or higher fines content sand). Geological testing like logging, dating, and sample scans are also useful in the unitization process.

A combination of *in situ* and/or laboratory geotechnical data can then form the foundation needed to derive a simplified ground model. Such a ground model may initially start as 1D unitization on locations across the site with interpolation between locations to create potential unit boundaries.

Layers within the ground assigned to the same unit can then be queried to better understand their properties across the site, and potential uncertainties for purposes of design.

In many projects, unit assignments for new boreholes and *in situ* tests can be based on a more refined ground model. A well-structured and comprehensive database for geotechnical analysis not only includes geotechnical data, but also geological data like soil stratigraphy and seismic data like interpreted horizons.

Figure 3 presents an overview of all grouping layers discussed in this paper. Some units may belong to multiple projects, typically when two or more projects, like wind farm sites, are located close to each other. In such cases, the units are shown in Figures 3 as a continuous pink box spanning both projects. Other units, such as *Clay A*, may share the same name across projects, but differ in their properties, like illustrated in the figure.

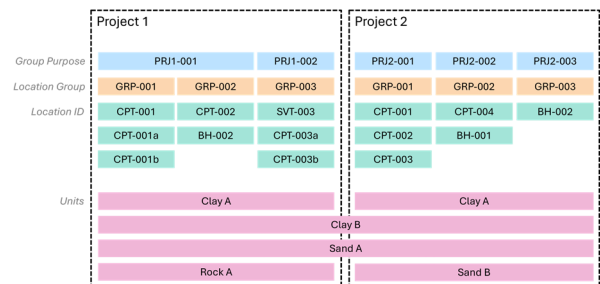


Figure 4-2 Overview of all layers of grouping. Note that the same units may belong to several projects.

5 DESIGN PARAMETERS

The final result of a site investigation project is usually design profiles showing geotechnical parameters with depth. Oil and gas structures have traditionally been more simple than offshore windfarms, with only a few design profiles needed per project. These can be derived manually in a reasonable time following the trend of the CPT data. Offshore wind farm sites are often comprised of 100's of individual locations, requiring a lot of time or manpower to process. In addition, these design profiles often need to be updated throughout the project when new data is available. Therefore, automated design line derivation is not only useful, but necessary. Proper data management combined with robust linear regression functions allow for fast and easy derivation of design lines. An interactive user interface allows for easy modification of the automatically derived lines where necessary, and for adding breaks in the linear profiles when the CPT trend changes (Figure 4). The user interface also serves as a first pass quality check of the automatically derived design lines.

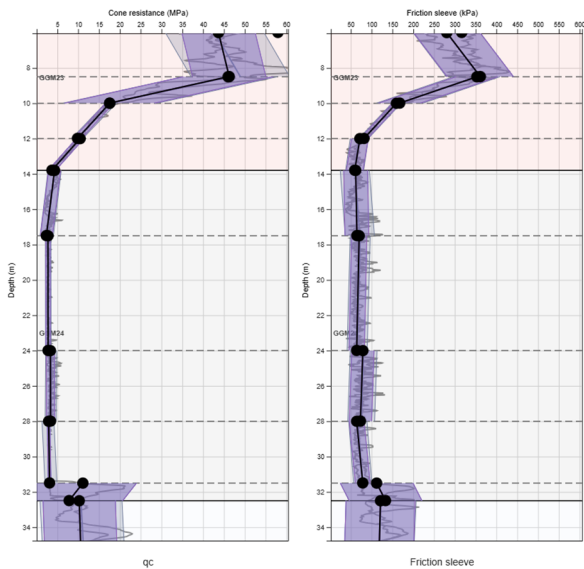


Figure 5-1 Interactive automated design profile derivation. Example data from Ten Noorden van de Waddeneilanden (TNW) (RVO, n.d., Sauvin, 2024)

Design profiles are derived on group purpose level, since each location group can be added to several group purposes. This means that, for example, it is possible to derive one set of design lines per location group, one per wind turbine footprint and one per wind farm zone.

For sites with limited or no site-specific data, such as during very early-phase feasibility studies, open-access government databases can provide valuable initial constraints on expected geotechnical conditions. Resources such as the Netherlands Enterprise Agency database (offshorewind.rvo.nl) and the UK's Marine Data Exchange

(marinedataexchange.co.uk) can be used to establish preliminary ranges for key geotechnical parameters. To fully benefit from these datasets, however, the information must be organized in a consistent and interoperable format.

Robust data management software is therefore essential not only for planning, executing, and interpreting ongoing site investigations, but also for making effective use of available open-access geotechnical data. The ability to share data across projects within the software is critical, provided that data governance, particularly with respect to data stewardship and distribution rights, is carefully maintained.

Utilizing open-source data can also be useful for advanced parameter calibration. The number of advanced tests is often limited within the project, and it may be beneficial to complement the project specific testing with available data. Gouvernec (2024) and Charles, J. A et al. (2023) presents a machine-learning based tool to predict shear stiffness degradation curves, trained on 500 stiffness degradation curves from previously published studies. Robust data management, combined with the API interface, allows for performing similar studies with limited time spent formatting and sorting the data. However, there will be an initial effort needed to upload literature and open-access data into the data management software.

5.1 Uncertainty quantification

All parameters have an inherent uncertainty. Well-structured databases permit comprehensive statistical analysis.

DNV (2021) recommends deriving design parameters for five sets of design conditions. The conditions, as well as the naming convention, is presented in Table 1. Different datasets may require different ways of calculating the five design conditions. This can easily be done by extracting simple statistical parameters like mean linear regression line and the R^2 value of your linear CPT fit through APIs. These can then be used in advanced statistical analyses.

Table 1 - Characteristic geotechnical parameter design conditions.

Condition	Name	Description
A	Low estimate	Characteristic value of lower tail of the distribution
B	Cautious low best estimate	Characteristic value of the lower tail of the mean distribution
C	Best estimate	Central unbiased estimate with lowest possible standard errors.
D	Cautious high best estimate	Characteristic value of the upper tail of the mean distribution
E	High estimate	Characteristic value of the upper tail

By grouping all data into soil and rock units, unit specific databases can be created through simple queries. These databases can be used to support prediction of soil parameters in locations where no geotechnical data has been collected but where geophysical data and geological understanding may indicate the presence of units and layers. Predictions can include the entire database in a rigorous way. Alternatively, more complex routines like hierarchical models can be applied to better quantify and constrain the overall uncertainty both at the site and potentially supported with data from projects with comparable geological settings (Bozorgzadeh et al., 2019). Robust statistical approaches are inevitable going into even bigger offshore sites with possibly less data available for design. Uncertainty assessments are also crucial when planning future investigations aiming to fill data gaps.

A jack-up is a type of mobile offshore unit with a floating hull and several extendable legs that can be lowered to seabed. Once the legs are firmly positioned at the seabed, the hull is jacked up above the water level, creating a stable working platform unaffected by wave action (Figure 3-1). Jack-ups are

commonly used for installation of offshore structures like offshore wind turbines. The footprint of the jack-up is significantly larger than the wind turbine footprint and does not necessarily have any location specific tests associated with the entire footprint. By combining the location-specific design parameters with a well-managed geotechnical database, a rigorous statistical framework and a full ground model or microsite, it is possible to obtain a bound on expected design parameters for a spudcan footprint, similar to what is shown in Vanneste et al. (2023). Such approaches can be used for various situations where location-specific in-situ data is not available. For example when doing an early phase assessment based on a limited dataset.

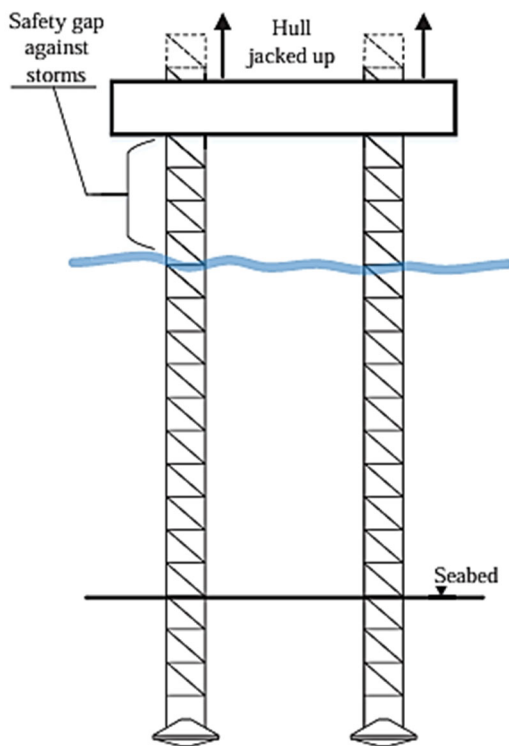


Figure 5-2 Principal sketch of a hulled-up jack-up, from Ragni (2016)

6 REAL-TIME ENGINEERING

Once all relevant data is stored in a structured, version-controlled database and grouped in a meaningful way, the foundation is established for true real-time decision-making and engineering. Additional data, whether from new investigation phases or completed laboratory testing programs, can be uploaded directly to the database, triggering immediate recalibration of design lines. These design lines can be exported in standardized formats and used with efficient foundation design calculation methods, such as those presented by Mohus et al. (2025), to rapidly assess whether the available data is sufficient for design. Such feasibility studies, based on rigorous statistical interpretation, can also indicate which units or locations are most important to reduce uncertainty in. They can highlight data gaps where additional sampling would *not* meaningfully improve or optimize the design. Examples of this could be a weak clay layer spanning across several locations in a pile design project. If such layer is never important for tip resistance of the piles and does not lead to a pile-run risk, it might not be very important to precisely characterize. In contrast, a sand bank encountered at the anticipated pile tip depth for several foundations could be beneficial to characterize in greater detail than what is standard practice.

It is essential to account for uncertainty, ensuring that design updates are based on statistically robust information rather than isolated datapoints. With smart data management, the entire cycle, from data upload to updated design verification, can be completed in seconds or minutes, enabling informed decisions to be made near real-time, even while offshore. For example, acquisition of additional CPT data with reduced uncertainty in key soil parameters can allow engineers to confirm adequacy of a pile design before vessel demobilization from a project site, avoiding costly remobilization and over-conservatism in design. It can also inform laboratory testing schedules to include additional tests

before sample disposal or remove extraneous tests if sufficient data is available. Even more advanced real-time studies can update necessary sampling depth based on necessary pile penetration analyses updated as information from the borehole is coming in real-time.

7 CONCLUSIONS

The accelerating pace and scale of offshore wind development demands geotechnical workflows that are both agile and robust. Central to achieving this is effective geodata management, which transforms raw measurements from field and laboratory into continuously updated, accessible, and reliable inputs for design. By establishing secure, version-controlled databases; enabling dynamic integration with analysis tools through APIs; and implementing meaningful grouping of data, it is possible to streamline every stage of the site investigation and design process.

The approach presented here enables rapid, data-driven decisions during ongoing campaigns, supports real-time engineering both onshore and offshore, and ensures that uncertainty is explicitly quantified and traceable. This not only reduces project timelines and costs but also improves the quality and transparency of foundation design. As offshore wind projects expand into deeper waters and more complex seabed conditions, these capabilities will be essential for meeting climate-driven deployment targets while maintaining safety, reliability, and environmental stewardship.

A well-structured comprehensive database opens for advanced parameter calculation methods, like machine learning based interpretation and Bayesian statistical methods. However, an initial effort to implement publicly available data in a data management system is necessary in order to utilize them.

While the presented geodata management framework offers significant improvements in efficiency, traceability, and accessibility, it is not yet fully integrated with other complementary datasets. In the current workflow, geophysical interpretations and measurements, such as bathymetry, sub-bottom profiles, and seismic attributes, are stored and processed in parallel systems rather than within the central database. As a result, opportunities for real-time cross-validation between geophysical and geotechnical data, within the presented workflow, are limited, and the full potential of combined datasets for improving subsurface characterization is not yet realized. Future developments should focus on establishing seamless data exchange between geophysical analyses and visualization platforms and the geotechnical database, enabling more comprehensive, multidisciplinary and multi-parameter interpretations and reducing uncertainty in ground models.

8 REFERENCES

- Bozorgzadeh, N.; Harrison, J. P.; Escobar, M. D. 2019. *Hierarchical Bayesian modelling of geotechnical data: application to rock strength*. *Geotechnique* 69 (12): 1056–1070. <https://doi.org/10.1680/jgeot.17.P.282>.
- Charles, J. A., Gourvenec, S., & Vardy, M. E. (2023). Recovering shear stiffness degradation curves from classification data with a neural network approach. *Acta Geotechnica*, 18, 5619–5633. <https://doi.org/10.1007/s11440-023-01879-4>
- Dimmock, P. S., Sharma, S., Tam, T., Tapper, L., Vanneste, M., Klinkvort, R. T., Forsberg, C. F., Kort, D. A., Griffiths, L., Bozorgzadeh, N., King, T. A., & Hill, A. W. (2025). *A ground modelling framework for offshore wind farm developments*. In C. Abadie, Z. Li, M. Blanc, & L. Thorel (Eds.), *Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG2025)* (pp. 1–8). International Society for Soil Mechanics and Geotechnical Engineering.

<https://www.issmge.org/uploads/publications/132/133/ISFOG2025-335.pdf>

- DNV. (2021). Recommended Practice: Statistical representation of soil data. Document No. DNV-RP-C207. Det Norske Veritas.
- European Commission, Secretariat-General. (2022). *Twinning the green and digital transitions in the new geopolitical context* (2022 Strategic Foresight Report) (Catalog no. KA-AP-22-001-EN-N; ISBN 978-92-76-53819-6; DOI 10.2792/022240). Publications Office of the European Union. Published 2022; released on EU publications website 1 September 2023
- European Environment Agency, 2024. *Harnessing offshore wind while preserving the seas*. [Online] Available at: <https://www.eea.europa.eu/en/analysis/publications/harnessing-offshore-wind-while-preserving-the-seas> [Accessed 11th August 2025]
- Susan Gourvenec (2024), Offshore geotechnical challenges of the energy transition, *Geomechanics for Energy and the Environment*, Volume 39, 2024, 100584, ISSN 2352-3808, <https://doi.org/10.1016/j.gete.2024.100584>. (<https://www.sciencedirect.com/science/article/pii/S2352380824000510>)
- Mohus, O., Moellenbeck, D., Klinkvort, R., Smith, V. B., and Bayton, S. M. 2025. *Streamlined workflows for offshore wind farm soil design parameter derivation and foundation concept screening*. Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2025), Nantes, France, June 9–13, 2025.
- Ragni, R. (2016). *Predicting the foundation performance of offshore jack-up drilling rigs in intermediate soils*. (Doctoral thesis, The University of Western Australia). UWA Research Repository. https://research-repository.uwa.edu.au/files/14410610/THESIS_DOCTOR_OF_PHILOSOPHY_RAGNI_Raffaele_2016.pdf
- Rijksdienst voor Ondernemend Nederland (RVO) (n.d.). Soil conditions at Borssele Wind Farm Zone. <https://offshorewind.rvo.nl/page/view/be898bea-672f-464c-bfaf-74666cb8c489/soil-tnw>, accessed: 27/November/2024.
- Sauvin, G., Vanneste, M., Vardy, M.E., Klinkvort, R.T., Forsberg, C.F. & Kirt, D.A. (2024), Integration of Geoscience Data – The TNW Offshore Wind Farm Case Study, Offshore Technology Conference, Houston, OTC-35476-MS, <https://doi.org/10.4043/35476-MS>.
- Vanneste, Maarten & Forsberg, C.S. & Klinkvort, Rasmus Tofte & Westgate, Z. & Forsberg, C.F. & Watton, Tim & Kassa, Henok M. & Skot-Hansen, J.. (2023). Data Integration Tailored to Assess Spatial Variability for Jack-Up Clearance Zone Assessment – Application to Offshore Renewables. 1925-1932. 10.3723/EGIM6139.