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Bridging the gap: a comparative insight into onshore and offshore ground modelling practices

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ABSTRACT: Creating site-specific, data-driven ground models presenting a three-dimensional spatial representation of geometric and geotechnical/geomechanical properties of the subsurface and defining the soil's and rock's behaviour under static and dynamic conditions is an essential aspect in the design of infrastructures across various industries, including construction, oil and gas, and renewables. Onshore and offshore ground modelling share a common purpose: to allow the conduction of geotechnical design that ensures adequate performance with respect to ultimate and serviceability limit states of structures and infrastructures. The definition of ground models relies on the acquisition and interpretation of data from multiple and diverse testing methods including geophysical and geotechnical investigations, and remote sensing technologies. Subsequently, data are interpreted using a variety of techniques, which are to be selected depending on the scope and aim of the project and on the type, quantity, and quality of available data. While the integration of geological, geophysical, and geotechnical data provides a best-practice approach in both onshore and offshore projects, significant differences arise due to distinct environmental conditions, specific geotechnical challenges, and logistic considerations (including areal extent). By examining these similarities and differences, this paper provides a structured comparative insight into ground modelling compilation process in onshore and offshore practices, with particular attention to the iterative nature of the ground model workflow endorsed by the second-generation Eurocode 7. The paper explores key topics such as data acquisition, interpretation, and technological barriers.

Keywords: Ground model; offshore geotechnical engineering; ground engineering; Eurocode 7; geotechnical design

1 INTRODUCTION

The geotechnical discipline has evolved significantly and continues to do so. Technological advancements, research, and real-world applications have fostered a shift in paradigm towards an increasingly data-driven and non-deterministic perspective. The two attributes are not coincident but work in synergy to exploit the unprecedented capabilities in data acquisition, analysis, interpretation and modelling brought by the ongoing digital revolution and to suitably model and process the very relevant uncertainties existing in geotechnical systems. This paradigm shift has also been reflected in geotechnical design codes, guidelines, and recommended practices, which have transitioned from their original deterministic formulation to prevalent present-day formats such as load-resistance factor design (LRFD), which inherently require the quantitative estimation of uncertainty (Uzielli, 2024). While this transition is not smooth, regulatory evolution is ongoing in many parts of the world. A notable example is the second-generation Eurocode 7 (EC7, under finalization), which highlights several bottom-line developments related to the increasingly central role of data and uncertainties. These are well-exemplified in the process defining the compilation of a project-specific ground model and, subsequently, of the geotechnical design model (CEN/TC250/SC7/WG1 - Task Group C2, 2024).

Within the broad context of the largest ongoing cooperation project at European level for the development of the next generation of Eurocodes, the European geotechnical community has reached a consensus regarding the definition and process of the ground model for geotechnical design purposes (Franzén et al., 2019). The second-generation Eurocode 7 defines the ground model as a *'site-*

specific outline of the disposition and character of the ground and groundwater based on results from ground investigations and other available data'. Based on this definition, the concept of the ground model has been further refined into two distinct models: the proper Ground Model (GM) including geology and a representation of factual data (Eurocode 7 – Part 2), and the Geotechnical Design Model (GDM, corresponding to the Geotechnical Design Basis (GDB) in the offshore market) concerning the geotechnical design of a structure and including the assignment of design parameters (Eurocode 7 – Part 1). In this conceptualisation, the GDM is the natural extension of the GM, although they are developed separately and on pseudo-parallel tracks. Therefore, it is recognised that the GM should be developed in conjunction with the Ground Investigation Report (GIR, corresponding to the Geotechnical Interpretive Report in the offshore market), which is linked to the GDM (CEN/TC250/SC7/WG1 - Task Group C2, 2024). Similarly, ISO 19901-10 ('Marine Geophysical Investigations') defines the GM as a three-dimensional representation of the (sub-)surface based any valid data (typically metocean, geology, geophysics, geotechnics, cultural, environmental), providing a geospatial understanding and summary of the static and active conditions which shall be updated when more relevant data becomes available. As such, it becomes a key decision making tool for geohazard and risk assessment, optimised data acquisition, layout plans, and specific foundation designs. We note that these definitions are aligned.

This paper provides a systematic comparison of typical approaches to ground modeling in onshore and offshore geotechnical practices. While the relationship between the GM and GDM is acknowledged, this paper limits its scope to methodologies, practices, and challenges involved in compiling and refining the GM and does not extend its analysis to the subsequent development of the GDM. The paper's structure reflects the operational flowchart presented in Figure 1, which outlines the conceptual principles and operational steps involved in defining the GM. Each stage of the process is examined critically in light of current practices and regulatory requirements. Key topics include strategies for data acquisition, interpretation, technological opportunities and challenges.

2 THE GROUND MODEL WORKFLOW

2.1 The ground model compilation process

The compilation of the GM involves the synergy between various geo-engineering disciplines (e.g., geology, morphology, hydrogeology, geophysics, geotechnical engineering, geomatics). The quality of the GM lies in the suitable quantification and representation of uncertainties, which is instrumental to the correct application of the regulatory framework, and which allows the rational quantification of the level of risk during the project lifecycle. The domains of onshore and offshore geotechnics are inherently different as they operate in markedly different environments, focus on different design concepts, and require at least partially different approaches to the planning and conduction of testing campaigns. The implementation of regulatory prescriptions may also involve different strategies, approaches, and methods for the compilation of the GM and, subsequently, to the conduction of geotechnical design.

EC7 is a regulatory demand for ground engineering projects, whereas many offshore projects are not bound to any regulatory codes. In the context of EC7, the conduction of geotechnical design follows an iterative process involving the initial formulation and the subsequent progressive refinement of an anticipated ground model (AGM) and a verified ground model (VGM).

The AGM details an initial conceptual hypothesis of the project site's subsurface conditions (e.g., stratigraphic profile, water depth/ groundwater conditions) as well as potential geohazards and engineering constraints. The AGM is compiled using information available from existing literature, extra-project investigations (morphological, geophysical, hydrogeological, etc.), as well as historical data. The AGM guides the planning of the project-specific geotechnical investigation campaign. The campaign must ensure the acquisition of a sufficient quantity of adequate and meaningful in-situ and laboratory testing data. Subsequently, data must be suitably interpreted (i.e., analyzed and integrated) to compile the VGM, which provides support to a 3D, quantitative representation of geotechnical parameters (i.e., strength, compressibility, permeability, etc.) as well as water depths/groundwater levels. The VGM must then be compared critically with the AGM to assess their mutual coherency and the utility of additional information brought by the site characterization process. If residual indetermination (related to the interpretation of the physical processes occurring at the site and/or to the uncertainty associated with the quantitative parameters) is too large with respect to regulatory requirements and/or subjective judgment, the following activities may be required: (1) the AGM is re-assessed critically using information from the last iteration of the VGM; (2) the VGM is refined following the critical re-examination of the AGM and through additional data acquisition and interpretation activities.

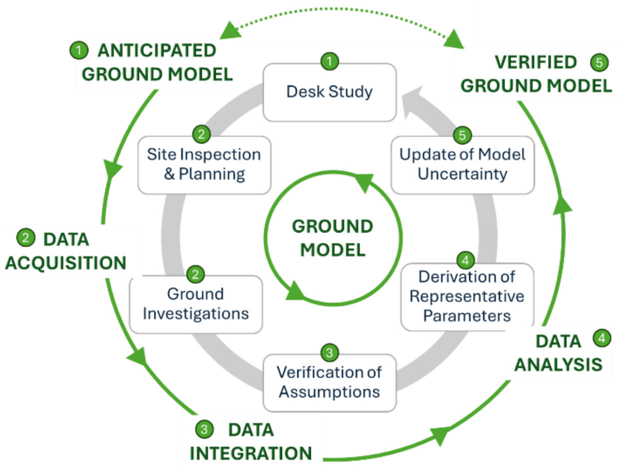

Figure 1. Conceptualisation of the ground model workflow: from the anticipated to the verified ground model

Each iteration of the process shown in Figure 1 brings additional information and refinement of the VGM until the final version of the GM is achieved.

2.2 From the ground model to the geotechnical design model

While the GM is suitably defined, the geotechnical design model (GDM) can be developed. The GDM builds upon the GM, but it is tailored specifically to the project's structural and functional needs. In the GDM, engineers define design values for geotechnical parameters by applying partial factors to representative values to account for residual uncertainties. The GDM incorporates assumptions about loads, boundary conditions, and limit states (such as ultimate and serviceability limit states) relevant to the specific project components, and directly informs calculations and design specifications aimed at ensuring compliance with regulatory requirements (e.g., Eurocodes).

The overall process intents to provide a suitable (functionally to the aim and scope of the project) and sufficiently reliable (in terms of the inevitable residual aleatory and epistemic uncertainties) geotechnical model to allow the correct implementation of design provisions. In this perspective, it is appropriate to operate with a workflow mindset during the entire project lifecycle. Figure 2 offers an overview of the design process workflow in both onshore and offshore projects, emphasizing the hand-in-hand workflow between the various processes (GM/GIR/GDM or GM/GIR/GDB), and the iterative approach within each project phase, where feedback and updates from earlier stages inform decisions in later phases. The chart integrates critical stages – ranging from initial concept and feasibility studies to detailed design, construction, and operation – with risk management and technical design.

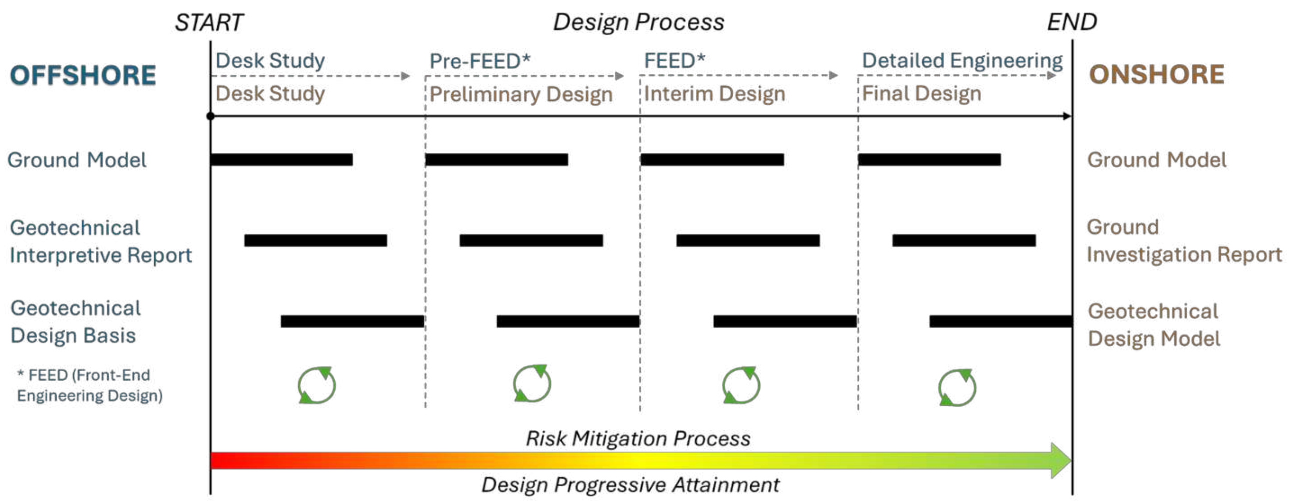

Figure 2 – Integrated representation of the risk-informed design process workflow: a comparison between onshore and offshore markets through the different project's phases

3 COMPARISON OF GROUND MODELLING PRACTICES

3.1 Anticipated Ground Model

Both onshore and offshore geotechnical practices rely on developing an anticipated (or "predicted") ground model (AGM). The process begins with a *desk study*, where existing information, such as geological maps, historical land use records (including the identification of existing infrastructures and unexploded ordnance), and previous project data, are gathered and reviewed to outline the expected geoengineering functioning of a site. Although inherently uncertain, this preliminary predicted model helps identify potential issues and guides subsequent steps for a structured approach to site investigation campaigns.

While the purpose of the AGM is consistent across the two industries, the methodologies and challenges differ significantly due to the unique conditions of each setting. Access to historical data in the offshore market is limited due to high costs, logistical challenges, and data fragmentation across organizations. Proprietary concerns, regulatory restrictions, and geological variability further hinder data availability. In contrast, onshore models generally benefit from a larger pool of historical data, due to easier site access, more frequent monitoring, and a longer history of exploration and development.

3.2 Data Acquisition

3.2.1 Site Inspection and Planning of Ground Investigations

In both onshore and offshore geotechnical practices, site inspection is essential for verifying assumptions from the AGM and guiding the planning of further investigations. Planning geotechnical and geophysical campaigns is essential for effective subsurface investigation and for safe, efficient, and cost-effective data collection. This targeted approach helps engineers select suitable equipment and methods tailored to the site's unique conditions (onshore or offshore). In onshore projects, planning often focuses on selecting drilling locations, sampling techniques, and in-situ testing methods that will best capture soil and rock properties relevant to the design. For offshore projects, the complexity increases, as planning must account for additional variables such as water depth, spatial extent of the sites, wave and current dynamics, and vessel logistics. Thus, offshore inspections are generally more complex, costly and equipment intensive.

3.2.2 Ground Investigations

Ground investigations (i.e., geotechnical and geophysical surveys) play a crucial role in the development of accurate ground models, as they provide the foundational data for interpreting the geotechnical functioning of a site both onshore or offshore. While the general principles of ground investigations are consistent in both contexts (such as the need for site characterization, geotechnical sampling, and laboratory testing) there are notable differences in approach due to the distinct environmental and logistical challenges.

Onshore investigations typically benefit from easier direct access for visual assessments and the ability to conduct more extensive borehole drilling, soil sampling, and geophysical surveys. In contrast, offshore investigations face challenges such as harsher environmental conditions, deeper layers of sediments to be investigated, and the need for specialized equipment (e.g., jack-up rigs or remotely operated vehicles for sampling and monitoring). Current regulations, such as the Eurocode 7 (EN 1997-1) and offshore-specific standards like ISO 19901-4, guide both practices, but offshore investigations often require stricter safety protocols and considerations due to the complexities of underwater conditions.

<u>Geotechnical Testing</u>

In-situ testing and borehole investigations, followed by laboratory testing, are fundamental practices in geotechnical engineering, providing essential information about the composition, lithology, strength, and deformation characteristics of soils and rocks. One of the most widely used in-situ techniques is the Cone Penetration Test (CPT), which provides real-time data on soil stratigraphy, strength, and stiffness. Boreholes are drilled to collect undisturbed soil and rock samples, which are then analyzed in a laboratory to determine key properties such as shear strength, consolidation characteristics, and soil composition. These methods are commonly used in both onshore and offshore geotechnical investigations, although the specific techniques and their application may vary depending on the site and the environment.

In the onshore domain, engineers often utilize a range of supplementary techniques to refine ground models and assess soil behavior under various loading conditions. The Ménard Pressure Meter (MPM) is one such technique, which provides valuable insights into the soil's deformability and stress-strain properties. Similarly, the Standard Penetration Test (SPT) is commonly used to obtain an estimate of soil density and strength. The Total Sounding Test (TST) is another technique used to measure soil resistance to penetration, providing data on its mechanical properties and aiding in the assessment of site-specific behavior under loading. In offshore applications, similar testing techniques may be adopted, but the use of specialized drilling rigs or equipment is often required due to the challenges posed by underwater environments.

Geophysical Testing

The geophysical techniques used for site characterization for onshore vs. offshore developments differ significantly in terms of the type of data collected and how it is integrated into the ground model development. These differences primarily stem from the challenges associated with data acquisition in each environment.

Onshore geophysical surveys typically involve a range of methods such as ERT (electrical resistivity tomography), GPR (ground penetrating radar), *P*-wave seismic refraction, surface waves analysis, (occasionally shear wave profiling) and magnetometer surveys, complemented with topographic surveys. One notable technique for large-area mapping is Airborne Electromagnetic (EM) surveys, which can effectively map features such as depth to bedrock, a critical parameter for infrastructure projects. These methods allow for relatively easy access to the site and direct in-situ data collection, providing valuable insights into the ground conditions. In contrast, offshore site characterization relies on a different set of geophysical techniques, due to the challenges – and opportunities – posed by the marine environment. Key methods include bathymetry (and co-registered backscatter), side-scan sonar, magnetometer, sub-bottom profiling, and various types of seismic surveys, such as extremely high-resolution reflection surveys (2D/3D). Offshore, typically, with a greater emphasis on 3D characterization, as it allows for a more consistent and robust understanding of the geological framework at a site, which is essential for assessing the conditions across the wide expanse of the seabed.

3.3 Data Interpretation

The primary objective of geotechnical interpretation of data is to determine the characteristic values of soil/rock properties, which are then used in the design process. These characteristic values are not fixed parameters but are determined based on the specific design situation, as they depend on factors such as the limit state considered, the failure mechanism, and the spatial variability of the specific parameter.

In the onshore domain, the geotechnical interpretation is typically informed by data from boreholes and in-situ testing, such as CPT and SPT, which provide quantitative information about the mechanical behavior of soils. The distance between sampling points and the variability in test results are important factors that influence the ground model. The GM is compiled by interpreting non-continuous geological dataset, which must be considered for a suitable geological characterization of the area of interest. In contrast, offshore site characterization benefits from the availability of continuous geological data, often derived from 2D/3D seismic surveys. This continuous data enables the development of a cohesive and spatially accurate GM. Furthermore, the combination of seismic data with geotechnical measurements from CPTs or boreholes allows for better correlation and validation of the ground model, leading to reliable and accurate soil property predictions, as demonstrated in studies such as Sauvin et al. (2019) and reports from industry experts such as the TNW case study (Sauvin et al., 2024), and as endorsed in the second-generation Eurocode 7.

3.4 Verified Ground Model

The verified ground model (VGM) is the final, refined representation of subsurface conditions. As shown in the GM workflow in Figure 1, the VGM should be continuously updated throughout the project's progression. Specifically, it should be critically compared with the AGM to assess their consistency and to evaluate the additional insights gained from the site characterization process, as well as from observations made during installation/construction.

4 DISCUSSION AND CONCLUSIONS

This paper has attempted to provide an articulate albeit concise insight into the shared principles and distinct challenges of ground modelling in onshore and offshore geotechnical practice. Onshore projects generally deal with more localized geotechnical issues, often at site-scale or pertaining to a spatially limited region. In contrast, offshore projects must address a wider range of factors, such as varying seabed conditions, water depths, wave, wind, and current data, covering extensive spatial scales (often hundreds of km^2) and complex environments. Based on these differences, ground modelling is developed according to methodologies tailored to the level of complexity of a specific project in the two industries. It is, however, common practice that the GMs are updated and maintained throughout the project's progression.

With regards to onshore projects, the second-generation Eurocode 7 introduces several key advancements related to the growing importance of data and uncertainties. In line with such regulatory developments, despite not being regulated in most cases, offshore practice also appears to adhere to current design principles and geotechnical paradigms, which are increasingly data-centric and non-deterministic. Hopefully, the more explicit treatment of aspects such as spatial variability and non-deterministic data interpretation and design which will be fostered by the second-generation Eurocode 7 may contribute to the increased awareness that geotechnical systems are always complex, and that ground modelling should duly account for this complexity irrespective of the spatial extension of a project.

Differences in project timelines and contractual realities further shape respective approaches to ground modeling in the onshore and offshore industries. Onshore projects are often characterized by long, stretched timelines, resulting in slower development. The extended timeframe from the tender award to project completion often leads to technological obsolescence, with infrastructures becoming outdated even before being commissioned. This prolonged project lifecycle can also impact the financial viability of the project. In contrast, the offshore market typically follows shorter contractual processes which are focused on early project planning (i.e., Front-End Engineering Design (FEED)). This compressed timeline allows for more agile technological development, which supports innovation and ensures that projects remain aligned with current technological advancements, benefiting both industry and society.

AUTHOR CONTRIBUTION STATEMENT

Patrizia Vitale: Conceptualization, Methodology, Investigation, Visualization, Writing- Original draft. **Maarten Vanneste**: Supervision, Validation, Writing-Reviewing. **Rasmus Tofte Klinkvort**: Supervision, Validation, Writing- Reviewing. **Marco Uzielli**: Conceptualization, Methodology, Validation, Supervision, Writing- Reviewing and Editing.

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