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Best practice approach to ground model optimised geotechnical location selection strategies

H. Eady* & C. Steven
Fugro GB Limited, Wallingford, United Kingdom
**h.eady@fugro.com*

ABSTRACT: A preliminary ground model (PGM) is a powerful tool at the onset of offshore site development projects. The PGM provides a comprehensive geological review detailing regional processes and expected sub-surface conditions to inform subsequent site investigations. Understanding the variability and engineering properties of the subsurface and identifying potential geohazards provides the framework to optimising the locations of intrusive geotechnical locations.
Key elements of the PGM include a gap analysis and integration of fit-for-purpose geophysical data to validate geological interpretations. The PGM guides the selection of geotechnical locations, prioritizing both operational safety and geological conditions, A well-distributed geotechnical investigation is advocated, whereby 70% of locations provide spatial distribution and 30% target specific features identified in the PGM. The concept of soil provinces is introduced to categorise areas with similar geotechnical properties, aiding in targeted and efficient sampling. This method ensures a balanced geotechnical campaign, capturing site-wide variability while focusing on critical geological features. The approach is exemplified by the IJmuiden Ver Wind Farm Zone. Here, the PGM identified seven major stratigraphic units and was used to optimise the geotechnical location strategy through a two-phased investigation. Similarly, the North Sea I Offshore Wind Farm Zone in Denmark faced challenges due to time constraints and limited site-specific data. Despite these limitations, the PGM approach allowed for effective geotechnical location selection, ensuring a realistic and comprehensive sample volume across the site. The methods demonstrated ensure a comprehensive ground model-led site characterisation, supporting informed engineering decisions, which mitigate potential geohazards and constraints.

Keywords: Preliminary Ground Model (PGM), Soil Provinces, Case Study, Offshore Site Investigation

1 INTRODUCTION

Planned offshore wind farm sites are increasing in size, as requirements for renewable energy increase in line with national climate goals. The Crown Estate reports a need for an additional 85 GW of offshore renewable energy than the 15 GW currently installed in UK waters (Crown Estate, 2024).

As a result of the increased demand for offshore wind, marine geotechnical site investigations need to provide a representative dataset of the ground conditions across a large spatial area for appropriate laboratory testing and site characterisation, within a sensible project certification, licensing and commercial schedule.

There are numerous requirements for the acquisition of safe and technically robust marine site investigation data that are codified into international standards and recommendations (OSIG, 2022 and ISO, 2021). Although common practice within offshore wind farm projects, the integration of a ground model into the planning phase for a marine geotechnical site investigation is not widely constrained.
A ground model is considered to be the state of knowledge document which details all geodata considerations and hazards at a proposed development, which aids future site engineering and design. The OSIG 2022 guidelines state that uncertainty related to the ground model principally relates to the quality of the geophysical model and the number of ground-truth boreholes available to calibrate that model. As a result, we make recommendations with regards to the approach to selection of the ground-truth locations that ensures cost efficiency in the acquisition phase and minimises the ground risk uncertainty once integration and ground modelling activities take place. Due to the time required to collect geotechnical locations and associated geotechnical test data, optimising the locations and sampling strategy of these datasets can provide significant time and cost savings to a proposed offshore development.

Normally geotechncial data is collected in two main project phases, initially site wide screening and a later infrastructure specific phase. These recommendations and paper focuses on the initial screening phase, however elements and learnings can also be applied to the later stage.

We conclude that a technically and commercially sensible site investigation which utilises a ground model approach ensures an appropriate spatial distribution and density of geotechnical locations but also achieves the correct characterisation of the sub-surface soil structures, which often do not fit with an even spatial distribution.

To achieve both of these aims, we demonstrate that a multi-phased "70:30" approach site investigation, built from a robust ground model is often the most appropriate for balance of geological sampling and spatial distribution, however, there will always be a need for site specific balancing of locations.

2 PRELIMINARY GROUND MODEL

A preliminary ground model (PGM) should be created at the start of a proposed offshore development, prior to site specific geophysical acquisition.

The PGM should contain a number of elements that ensure an optimal specification for a follow on fit for purpose geophysical and geotechnical site investigation, including but not limited to analysis of: bathymetry and geomorhology, obstructions at seafloor and assessment of geological variability and hazards. The PGM should provide a detailed geological review of soil conditions that are expected to be present across a site which are used to calibrate the interpretation and siting of subsequent testing locations and line plans.

2.1 Geological Review

A geological review, as part of a preliminary ground model (PGM) will detail the regional processes that have occurred within the depth of interest for the site investigation and proposed infrastructure influence depth. The geological review will reveal what the expected sub-surface lithologies and formations may be, providing insight to the engineering properties and variability of the sub-surface. Further contextualising the depositional and post depositional geological processes will provide insights to the variability within the expected geology and whether geological hazards can be determined. An example of this may be identifying that sands within a study area have been deposited via a shallow marine environment, and therefore are likely consistent in there geotechnical properties, or if they are fluvial and may be channelised and have a greater variability in geotechnical properties.

As part of the geological review, processes can also be understood with respect to geohazards that may also need to be considered for location selection in future surveys, such as organic rich areas that should be targeted for characterisation.

Understanding the current state of knowledge of the datasets that are available is a key stage for the recommendation of locations. The likely resolution of spatially delineated features needs to be considered.

2.2 Variability Assessment and Gap Analysis

After likely conditions are identified, a review of the likely variability of the units and the implications with respect to geotechnical conditions should be applied. This process includes reviewing the depositional provenance associated with the expected lithologies and then understanding how that may result in conditions that will be laterally consistent or either randomly variable, or variable based on defined geomorphological processes. This information is key to understanding the requirements for the planned location selection work.

At this stage, a gap analysis is recommended. It allows for the determination of the current state of the surface and sub-surface conditions in relation to the requirements of the proposed infrastructure, and therefore influences the choices made at site investigation and laboratory testing phase. Gap analyses and variability assessments should be conducted throughout the project life-cycle to ensure that the state of knowledge is reliable and current, updates to these workflows are best undertaken following integration of any site specific geophysical or geotechnical data.

2.3 Integration of Geophysical Data

Geophysical data which is fit for purpose should be integrated into the preliminary ground model with the aim of confirming the conclusions made in the geological review, and as a vital input into the variability assessment and gap analysis.

The interpretation of the geophysical data should subsequently build on the findings in the PGM and forms the most critical input dataset for optimising geotechnical locations.

3 LOCATION SELECTION STRATEGY

Geotechnical location selection should consider the findings of the PGM in order to optimise the effectiveness of any field campaign. Careful considerations should be made with respect to 1) acquisitional safety and 2) geological ground conditions.

Acquisitional safety considerations include siting on seismic survey track-lines away from magnetometer contacts, avoidance of seafloor infrastructure and debris, and ensuring ALARP

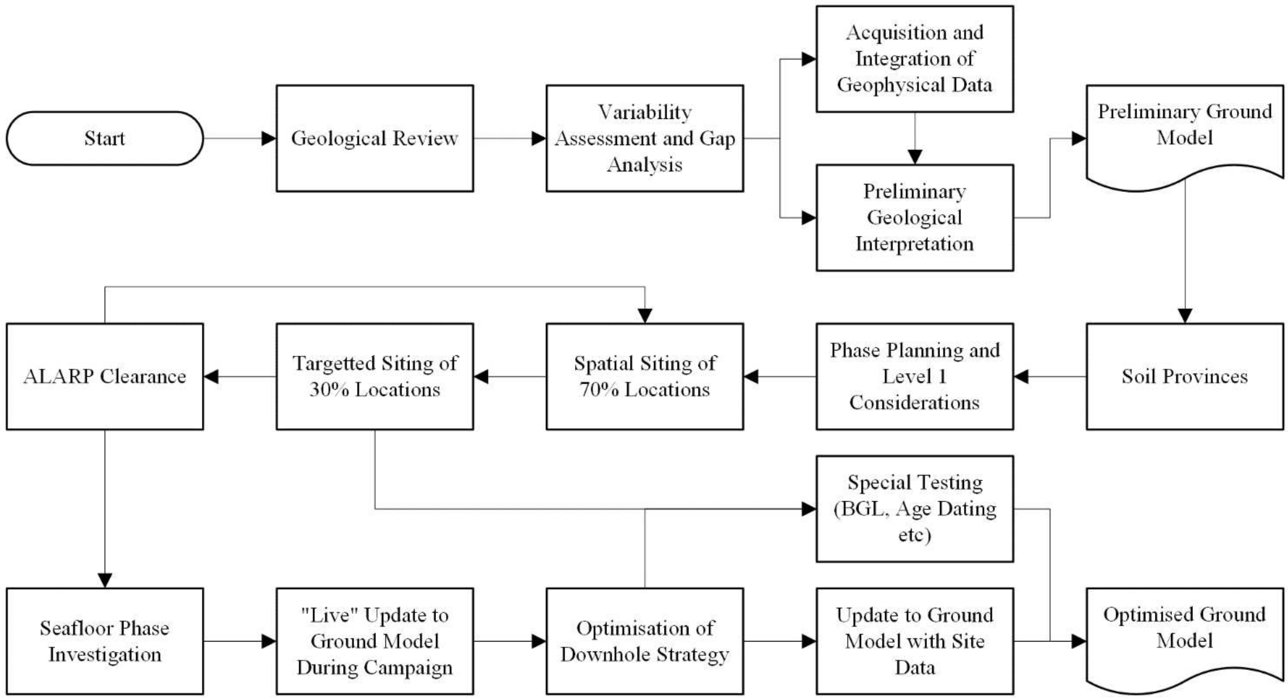

Figure 1: Idealised workflow for best practice approach to geotechnical location selection using a geological ground model framework

clearances are present for each proposed location. These considerations must be priority before assessing locations for their geological ground conditions, for which the rest of this paper discusses.

The approaches below are best suited to a phased geotechnical site investigation, i.e, the first phase being a seafloor cone penetrometer (CPT) and vibrocore (VC) survey, and the second phase consisting of borehole downhole drilling and sampling techniques. The preliminary ground model should be updated between each phase, in order to refine the variability assessment and gap analysis, provide more refined geological and geotechnical assessments and therefore inform the second and future phases of location planning.

3.1 Soil Province Approach

The first key step in optimising geotechnical locations in order to adequately represent the geological soil conditions is the derivation of soil provinces and associated predicted stratigraphic profiles.

Soil provinces should delineate the proposed development site into a series of “similar” soil conditions (geotechnical properties and behaviours), acquisition properties and seafloor constraints. For example, hypothetical *Soil Province A* could be an area of the site, identified to be thick clay stratigraphy underlying a mobile sandy seafloor, whilst *Soil Province B* could be a delineation of channelised stratigraphy which erodes into deeper sediment and introduces an area of increased variability.

This classification helps in scoping the investigation strategy to the specific conditions of each province, ensuring that both the spatial distribution and targeted sampling are optimised for the local geology. Investigation locations can be prioritised within each province, balancing broad coverage with the need of detailed investigation in areas of interest.

Eady et al. (2023) demonstrate at the IJmuiden Ver Wind Farm Zone that the generation of a PGM integrated with geophysical data and subsequent derivation of soil provinces before an intrusive site investigation increased the resolution of the ground model and further derived products due to optimal location siting.

3.2 70-30 Approach

Balancing the requirements for a spatially well distributed geotechnical campaign with identified geological complexity is a difficult challenge. For offshore windfarm development, wind-turbine generators (WTG’s) are often spaced with an even distribution, with governance for performance and safety dictating how far apart they must be. However, this does not correlate with the distribution of localised geological features and their inherent variability of engineering properties.

Maintaining a broad spatial distribution of geotechnical locations is essential for capturing the variability of subsurface conditions. This approach helps in identifying regional stratigraphic layering and morphology and changes in site wide soil and rock properties, which are critical for the concept and feasibility of different foundation types. By allocating ~70% of the geotechnical locations to systematic pattern, driven by the primary soil provinces identified, the data collected provides a representative overview of the site's geotechnical characteristics, reducing the risk of missing significant subsurface variations that could impact the operational design and safety of the project.

The remaining ~30% of boreholes should be strategically placed to sample specific geological features identified during the preliminary ground model, soil provinces and geophysical interpretation. These features may include areas with unique soil properties that require detailed analysis, which aren't however, site wide. Targeted sampling allows for a more in-depth understanding of these critical areas, providing data that can inform more precise engineering decisions and geo-risk assessment. Examples of such targeted features could be buried paleochannels, layers of peat or mass transport deposits.

4 CASE STUDY EXAMPLES

4.1 Southern Bight, Offshore Netherlands

IJmuiden Ver Wind Farm Zone (IJVWFZ), a proposed 6 GW development, is situated within a dynamic area of the Southern North Sea, known as the Southern Bight, which underwent ground modelling and geo-data acquisition as part of the Dutch government pre-bid tender process. It is split into IJmuiden Ver Alpha and Beta and IJmuiden Ver Gamma.

IJmuiden Ver Alpha and Beta (IJV-AB) is characterised by a Holocene seafloor, which exhibits a range of geomorphological features, overlying a series of onlapping, lensing and channelised deposits dating back to the mid-Pleistocene, within a typical wind farm depth of interest (Rijsdijk et al., 2005). Whilst the regional geology of the Dutch sector of the North Sea is relatively well defined, there are few intensive site studies detailing the complex stratigraphy from the Pleistocene to Holocene, in particular the orientation and extent of palaeo-channels in the sub-surface.

The challenge for ground modelling and geotechnical location selection at IJV-AB is the geographic size of the site, at 439 km^2, with a defined number of boreholes and CPTs available for use during a geotechnical campaign, which need to be integrated with a defined geophysical survey spacing and geological and geotechnical parameters extrapolated between datasets across the site.

The site survey campaign was optimised using the steps demonstrated in this paper, with a pre-survey desk study (Thal et al., 2019) used to inform geophysical survey interpretation (GEOxyz, 2020) and subsequently form the PGM.

The PGM identified that at IJV-AB, seven major stratigraphic units which represent sand and clay beds deposited under shallow to open marine to glaciofluvial, with deep incisions and channelisation from the late Pleistocene to present day (Fugro, 2023 and Eady et al., 2023).

The geotechnical location strategy at this site utilised the 70-30 approach in a two-phased investigation to ensure that a good spatial coverage was acquired but the key geological features, in particular, channelised and lensing structures were adequately characterised and mapped. The soil provinces developed as part of the PGM were the key tool for ensuring that the appropriate soils were sampled during this process.

The first phase of the investigation was a seafloor CPT and Vibrocore campaign which included 385 CPTs and 186 Vibrocores (Fugro 2021a,b). Seafloor sampling data was assessed and unitised in accordance to the PGM in order to update the working ground model and inform decisions for downhole survey.

The downhole survey phase was optimised by assessing shallow CPT termination and where data suggested that there are engineering critical layers that require lab testing. Further considerations of site wide conditions, geological features and geohazards were characterised by special testing including borehole geophysical logging and biostratigraphic age dating, to further improve and optimise the subsequent ground model. In total 151 boreholes were sited, paired with an existing seafloor CPT (Fugro 2021a,b).

Table 1: Density of data in Dutch wind farm zones, IJmuiden Ver Alpha and Beta is highlighted in blue

Wind Farm Zone	**Size [km^2]**	**CPTs per km^2**	**BH per km^2**
Hollandse Kust Zuid	356	0.29	0.16
Hollandse Kust Noord	304	0.25	0.09
Hollandse Kust West	224	0.53	0.21
Ten noorden van de Waddeneilanden	120	0.71	0.28
IJmuiden Ver Alpha and Beta	439	0.82	0.34

4.2 North Sea I OWFZ

The North Sea I site is part of Denmark's push for greater offshore wind capacity before 2030. The North Sea I site is currently divided into three blocks, A1, A2 and A3, and lies of the west coast of Jutland between the Thor OWF to the North and the Horns Rev 3 site to the south. Like much of the North Sea coast of Denmark, the site is characterised by deep tunnel valley features formed during the Elsterian glaciation. Above these sediments are variable glacial and interglacial sediments from the Saalian to present day. The site exists in an area where a good understanding of the geological processes can be determined however there is a time pressure on the data collection work owing to the scheduling of tendering on the sites.

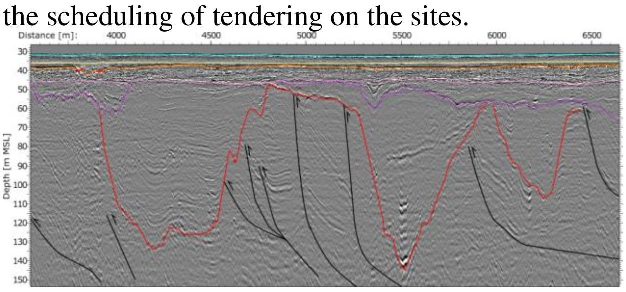

Figure 2. Example of mapped tunnel valley areas in 2DUHR data

A key constraint in the selection of sample locations for the North Sea I site was the availability of site specific data. Due to time limitations on collection of datasets, there was the requirement for selection of geotechnical sampling locations prior to the completion of the geophysical survey. In total 90 % of the geotechnical locations were required to be pre-selected before site specific data were available. The remaining 10% would be located on a "coarse" 2DUHR survey that would be completed prior to the rest of the survey.

In total approximately 300 seafloor CPT locations and 140 geotechnical sampling BH locations would be selected across the North Sea I (and adjacent subarea). Despite the limited datasets available, consistency in the approach and use of ground model work allows for the end sampling regime to be consistent with the other case study example.

Initial review of the site showed the significance of glacial tunnel valley features that transect this area of the North Sea in a typically N-S orientation. Secondary to this was the presence of large early Holocene fluvial channels. Indicators of these can be seen in regional seismic datasets acquired in the area and in literature (Huuse and Lykke-Andersen, 2000), By following the process outlined in Section 3, it was identified that these units likely represent the greatest spatial variability and therefore location selection should focus on ensuring that there is sufficient material available to characterise them.

Shallow Holocene channels were identified to likely have geotechnical variability based on the position with respect to the channel thalwegs, with additional variability present

A PGM was developed using the incomplete geophysical dataset Although this made identifying the exact lateral and horizontal variability of the site more challenging, it was still possible to assign sample locations utilising the PGM, highlighting the strength of this approach despite limited datasets. A balanced approach, where 70% of borehole locations are dedicated to maintaining spatial distribution and 30% are focused on sampling specific geological features, is recommended to optimise data collection and ensure that a realistic and comprehensive sample volume is acquired across the site.

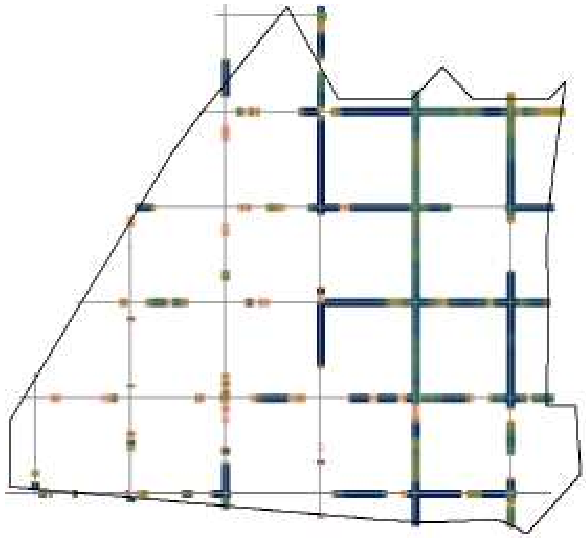

Figure 3. Depth to base of mapped Tunnel valley unit across site

5 CONCLUSIONS

The implementation of a Preliminary Ground Model (PGM) in offshore development projects provides significant scope for optimisation of future data acquisition. Firstly, PGMs enhance georisk mitigation by providing a detailed understanding of subsurface conditions and potential geohazards.

PGMs aid the optimisation of costly geotechnical site surveys by integrating geophysical and geotechnical data to ensure that each geotechnical location has a defined purpose in characterising the subsurface, with the derivation of soil provincing This approach ensures that geotechnical investigations are comprehensive and cost-effective, reducing unnecessary expenditure and maximising the use of allocated site investigation budget and equipment requirements.

The detailed ground models produced by PGMs inform better design and engineering decisions for foundations, anchors, and other infrastructure components. This results in structures that are better suited to the specific geological conditions of the site, enhancing their stability and longevity. The PGM approach is adaptable to site-specific challenges, such as time constraints or limited data availability. This flexibility ensures that projects can proceed with a high degree of confidence in the ground conditions. Finally, comprehensive ground models support regulatory compliance by providing detailed documentation of site conditions and the measures taken to address potential risks.

Overall, the use of PGMs in future offshore projects promises to enhance safety, efficiency, and reliability, ultimately leading to more successful and sustainable developments.

AUTHOR CONTRIBUTION STATEMENT

H. EADY: Conceptualization, Formal Analysis, Methodology, Visualisation, Writing – Original Draft, Writing – Review and Editing
C. STEVEN: Investigation, Validation, Writing – Review and Editing.

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