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

ISBN 978-2-85782-758-0

A ground modelling framework for offshore wind farm developments

P. S. Dimmock*
NGI, Perth, Australia

S. Sharma, T. Tam, L. Tapper
NGI, Perth, Australia

M. Vanneste, R. T. Klinkvort, C. F. Forsberg, D. A. Kort, L. Griffiths, N. Bozorgzadeh
NGI, Oslo, Norway

T. A. King
NGI, Houston, USA

A. W. Hill
BP America, Houston, USA

**paul.dimmock@ngi.no (corresponding author)*

ABSTRACT: Alignment between stakeholders on a ground modelling framework for offshore wind farm developments would improve consistency, quality, and efficiency of ground models. This will result in more effective management and mitigation of geo-engineering risk, and through targeted reduction of uncertainty of ground conditions provides the project with geo-engineering optimisation and performance opportunities. This paper proposes a framework that can be referenced by all project stakeholders, i.e., Clients, Consultants, Contractors and Certifiers. The framework consists of definition, purpose, terminology, content & structure, and deliverables. Key threads are emphasised, including expertise, data types, data integration, and uncertainty. The purpose of ground modelling is framed against geo-engineering performance criteria and alignment is sought on the use of key terms. A pyramid is used to convey the content and structure of the ground model, and deliverables are clearly distinguished. The various geo-expertise required to build robust ground models are highlighted and their roles explained. The different data types associated with the 3G's (Geological, Geophysical, Geotechnical) of ground modelling are introduced, and options for data integration are clarified and presented in the context of project cost-benefit. The various elements of uncertainty are identified, and appropriate phasing and scoping of data acquisition is highlighted to reduce uncertainty in ground conditions in step with progression of project geo-engineering.

Keywords: Ground modelling, integration, uncertainty, geo-engineering

1 INTRODUCTION

A ground model is defined here as a 3D representation of the ground (surface and subsurface), and processes that may change the ground, over a development area or area of interest. The ground model is based on geological understanding, plus the integration of geological, geophysical and geotechnical data, and may incorporate other geo-data of relevance. The ground model must also capture uncertainty in ground conditions.

This paper proposes a framework for ground modelling that can be used as a basis for alignment between stakeholders on how to build and use ground models for offshore wind farm development. The intent is that this would benefit offshore wind projects by improving consistency, quality, and efficiency in ground model development. The resulting ground model will then provide greater opportunities for geo-engineering optimisation and to reduce project risk.

2 GROUND MODEL PURPOSE

The ground model provides understanding of the ground, geospatial and temporal, required to satisfy geo-engineering performance criteria for the development such as:

- Installation – safe installation to tolerance.
- In-place performance – satisfying engineering performance criteria in operation and for design events.
- Removal – safe decommissioning and retrieval.

The ground model is the basis for effective management and mitigation of geo-engineering risk, and through targeted reduction of uncertainty of ground conditions provides the project with geo-engineering optimisation and performance opportunities.

3 TERMINOLOGY

Some key terms used in the ground model, and in relation to geo-engineering input derived from the ground model, are provided below:

- **Geo-engineering** – project engineering related to the ground including foundation design, cable design, and infrastructure layout.
- **Geo-engineering constraint** – an existing ground feature that is a static engineering constraint to the development and is addressed by routine project engineering (Dimmock et al., 2023).
- **Geohazard** – a ground process which is a risk to the development and is addressed by project risk management frameworks (Dimmock et al., 2023).
- **Geotechnical parameter** – geotechnical property, usually defined per ground unit.
- **Ground processes** – causes of change to ground conditions.
- **Ground and Material** – generic terms covering the full spectrum of sediment through to rock, this is the founding material for the development.
- **Seafloor** – refers to the top 'facet' surface of the ground offshore
- **Subsurface** – ground below the seafloor
- **Unit** – subdivision of a ground model for the purpose of characterising geotechnical uncertainty, typically defined by seismic stratigraphic interpretation combined with geotechnical data and geological understanding.

4 CONTENT

The content for a ground model should follow a pyramid structure as depicted in Figure 1. This shows not only the ground model but also the geo-engineering input derived from the ground model. In this distinction a ground model, for example, includes probabilistic distributions capturing uncertainty of geotechnical parameters within units. However, geotechnical parameter design profiles derived from these distributions for a specific engineering purpose may be regarded as 'geo-engineering input'. The same distinction applies to geo-engineering constraints, which are surface and subsurface features from the ground model affecting geo-engineering; and geohazards which are ground processes affecting geo-engineering.

Content	Dependency	
12. Recommendations	8 – 11	Next steps
11. Geo-engineering	8 – 10	Design, layout etc.
10. Geohazards	7	Geo-engineering inputs
9. Geo-engineering constraints	5 – 6	
8. Geotechnical parameters for design	5 – 6	
7. Ground processes	3 – 4	Ground model - interpretation
6. Ground subsurface (incl. geotechnical parameter distributions across units)	3 – 4	
5. Ground surface (Seafloor)	3 – 4	
4. Site data	Client supplied + Publicly available data	Ground model - background and input
3. Regional setting	Literature review	
2. Purpose	Development plans	
1. Introduction	Scope of work	

Figure 1. Pyramid structure for ground model, geo-engineering input and geo-engineering

5 DELIVERABLES

5.1 Ground model

Ground model documentation can consist of the following deliverables (reference is made in brackets to corresponding sections of the ground model shown in Figure 1):

- Ground model report (GMR) (§ 1 – 7).
- Geotechnical interpretative report (GIR) focusing on geotechnical parameter distributions across units (linked to § 6 of GMR),
- Specialist studies, e.g., ground processes (linked to § 7 of GMR).

Digital deliverables associated with the ground model can include the following:

- GIS project – infrastructure layout, geomorphology, surficial material, seafloor and subsurface features, ground processes, unit depth and thickness.
- Subsurface seismic interpretation project – representation of subsurface data, interpretation of units, together with all available in-situ data.
- Interactive tools for visualisation of the ground model – including a 3D viewer, cross-section viewer and a log viewer.
- Geotechnical property prediction intervals (i.e., capturing uncertainty) – these may be based on correlations between geotechnical and geophysical data formed by Level 2 and 3 data integration, as described in Section 8. An example is provided by Sauvin et al. (2019).

5.2 Geo-engineering inputs

Geo-engineering input derived from the ground model may comprise the following documentation (reference is made in brackets to corresponding sections of the ground model shown in Figure 1):

- Geotechnical design basis (GDB) (§ 8 – 10) – includes geotechnical parameter design profiles for stratigraphic units at facility locations plus geo-engineering constraint and geohazard data for ground features and processes, respectively, that need to be accounted for in geo-engineering design.
- Geohazard assessment reports and Geohazard risk register (linked to § 10) – these may not be provided to the geo-engineering designer or contractor since their primary purpose is for risk management by the client. However key information that is to be accounted for in geo-engineering design may be referenced by the GDB.

Digital deliverables associated with the geo-engineering input can include the following:

- Geotechnical parameter design profiles for units at facility locations in tabular and graphical format.
- Geo-engineering constraint register and data in tables/ graphs as appropriate, GIS representation as appropriate.
- Geohazard risk register, geohazard data, geohazard vulnerability maps, GIS representation as appropriate.

6 EXPERTISE

A robust ground model can only be achieved through integrating input from the 3G's, namely:

- **Geological data/ knowledge** to inform the regional setting, particularly covering formative processes.
- **Geophysical data** to image the seafloor and subsurface, including extracting quantitative information from this data (e.g., seismic attributes, or inversion such as Vardy et al., 2018).
- **Geotechnical data** to calibrate the ground model at specific locations and to provide the link to geotechnical properties.

Alignment across the 3G's significantly increases confidence and reduces uncertainty in the resulting ground model.

Expertise in the Geo-team must cover Geology (including Geomorphology), Geophysics and Geotechnical Engineering to interpret and integrate input from the 3G's. Effective integration requires a high level of cross-disciplinary understanding; hence all members of the Geo-team should have sufficient understanding of the data obtained and interpreted by the other disciplines. Data analysis is also an important capability to have in the team.

7 DATA TYPES

Typical geophysical and geotechnical/ geological data types for input to ground models are introduced in

Table 1 and Table 2, respectively. The tables are not exhaustive. The tables describe each data type and its purpose for the ground model.

Table 1. Geophysical data

Type	Description	Purpose
Seafloor		
Single-beam echosounder (SBES)	Seafloor topography	Confirmation of water depths below the vessel
Multi-beam echosounder (MBES)	Seafloor topography and attributes	High resolution map of the seafloor and seafloor topography (e.g., depth, slope, dip direction)
Backscatter (MBES)	Surface reflectivity	Seafloor material type, detect objects and debris
Side scan sonar (SSS)	Surface reflectivity	Seafloor texture and type, detect objects and debris
Subsurface		
Sub-bottom profiling (SBP)	Subsurface reflectivity	High definition of near-surface sediment stratigraphy and near-surface features
Multi-channel 2D Ultra-High Resolution Seismic (2D UHRS)	Subsurface reflectivity and seismic attributes	2D definition of subsurface stratigraphy and subsurface features
Multi-channel 3D Ultra-High Resolution Seismic (3D UHRS)	Subsurface reflectivity and seismic attributes	3D definition of subsurface stratigraphy and subsurface features
Seismic refraction profiling	Subsurface velocity profiles	Characterise changes in density or hardness of stratigraphic units
Magnetometer	Near-surface magnetic field anomalies	Detection of ferromagnetic debris or UXO
Borehole geophysical logging	Natural gamma, P-wave and S-wave velocity, caliper	Natural gamma for lithology, P-wave and S-wave velocity for in-situ measurement of stiffness
Multi-sensor core logging (performed on geotechnical/ geological samples)	P-wave velocity, gamma density, natural gamma, magnetic susceptibility, electrical resistivity	P-wave velocity for stiffness, gamma density for bulk density, natural gamma for lithology, magnetic susceptibility for amount of magnetic material, electrical resistivity

Table 2. Geotechnical/ geological data

Type	Description	Purpose
Cone penetration test (CPT)	Cone penetration test deployed from seafloor system, or downhole system	In-situ measurements of cone resistance, sleeve friction and pore pressure, which can be correlated with various laboratory tests and with various engineering properties
Seismic cone penetration test (SCPT)	Cone penetration test with seismic velocity measurement	In-situ assessment of shear wave velocity
Sediment sampler (Borehole)	Downhole system to acquire sediment samples	Recover sediment samples for geotechnical/ geological logging and various laboratory testing
Rock corer (Borehole)	Downhole system to acquire rock samples	Recover rock samples for geotechnical/ geological logging and various laboratory testing
Piston core	Gravity sampler deployed from side of vessel	Recover near-surface sediment for geotechnical/ geological logging and various laboratory testing
Vibrocore	Vibration sample deployed from side of vessel	Recover near-surface coarser sediment for geotechnical/ geological logging and various laboratory testing
Box core	Box sampler deployed from side of vessel	Recover surficial sediment for geotechnical/ geological logging and various laboratory testing

8 DATA INTEGRATION

The interpretation of geophysical and geotechnical data should always be underpinned by geological data/understanding as this will increase confidence in the ground model.

There are various levels at which subsurface geophysical data can be integrated with geotechnical data. Three levels may be distinguished based on the extent to which the geophysical data is leveraged. The levels are as follows:

- **Level 1:** seismic unit boundaries and facies are calibrated with geotechnical data.
- **Level 2:** Level 1 + correlate geotechnical data to seismic data attributes.
- **Level 3:** Level 1 + 2 + correlate geotechnical data to inverted seismic data attributes.

Progression through the integration levels should be on the proviso that it will reduce uncertainty in prediction of ground conditions. This is a function of the density and quality of both geophysical and geotechnical data, which in turn depends on the suitability of geophysical and geotechnical data acquisition and processing approaches for a given geological setting. Project schedule and budget must accommodate the progression. Furthermore, the benefit of progressing through the integration levels in terms of uncertainty reduction for geo-engineering and geo-risk management should be weighed against the additional integration time and cost.

For 2D subsurface seismic data the result of interpretation and integration along the 2D seismic lines needs to be propagated between seismic lines to fill the 3D ground model by a spatial interpolation algorithm such as kriging. For 3D subsurface seismic data both interpretation and integration are performed in 3D.

9 UNCERTAINTY

Uncertainty in prediction of ground conditions at any point within the 3D ground model stems from geophysical parameter uncertainty, geotechnical parameter uncertainty, plus model uncertainty and residual variability associated with integration of data, and spatial propagation of predictions.

The geophysical and geotechnical parameter uncertainty is affected by data quantity and measurement error. Uncertainty in the parameters reduces as more data is acquired, processed and interpreted. Model uncertainty and residual variability are a product of model fitting and reflect the imperfection of the model.

The objective of geophysical and geotechnical data acquisition, processing and interpretation is to provide sufficient constraint (i.e., sufficient uncertainty reduction) on geo-engineering inputs for the development, namely: geotechnical parameters for design per stratigraphic unit, geo-engineering constraints, and geohazards. Geological data/ understanding is crucial to anticipate geospatial variability for the purpose of planning geophysical and geotechnical data acquisition and processing.

Generating uncertainty intervals with depth for geotechnical parameters within each unit requires correlations between geotechnical laboratory test data and corresponding in-situ geotechnical data. The objective is to obtain sufficient laboratory and in-situ data in the various units and materials affecting geo-engineering across the site to improve the predictability of ground conditions, i.e., reduce the residual variability captured by probabilistic models. Appropriate grouping of data, e.g., based on stratigraphic unit and material type, to form the correlations is important to improve the predictability. Predictability can be enhanced by exploring normalisation relationships premised on underlying drivers of geotechnical behaviour such as effective stress and density (and proxies to these parameters) to facilitate broader grouping of data.

Probability distributions should be used to represent uncertainty for prediction of geotechnical parameters at any point within the 3D ground model. Guidance on this is provided in DNV (2021).

Best practice in applied data analysis should be adopted to improve the model fit, including model checking, model comparison and model selection.

10 PHASING

Phasing of geodata acquisition is intended to reduce uncertainty in the ground model to satisfy geo-engineering input requirements for the project design stages (see Figure 2). Table 3 shows typical maturity of the ground model and geo-engineering input associated with each design stage. Table 4 shows the site data from each of the 3G's that typically underpins geo-engineering input for each design stage.

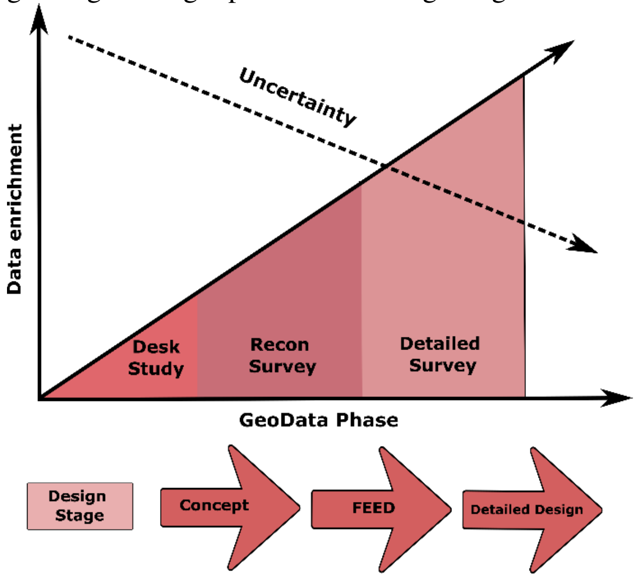

Figure 2. Uncertainty reduction through phased geodata acquisition for geo-engineering input to project design

Table 3. Evolution of ground model, and geo-engineering input, with project engineering design stage

	Concept	FEED	Detailed Design
Site data available	Legacy datasets, public domain information, possibly Reconnaissance SI data	Legacy datasets, public domain information + Reconnaissance SI data + possibly Detailed SI data	Legacy datasets, public domain information + Reconnaissance SI data + Detailed SI data
Ground model	Desk study (initial ground model), Level 1 integration	Intermediate ground model, Level 1, 2 or 3 integration	Final ground model, Level 1, 2 or 3 integration
Geotechnical parameters	Unit-based geotechnical parameter design profiles	Unit-based geotechnical parameter design profiles + Location-specific (if SI data sufficient)	Unit-based + Location-specific geotechnical parameter design profiles
Geo-engineering constraints	Initial geo-engineering constraint register	Intermediate geo-engineering constraint register	Final geo-engineering constraint register
Geohazards	Initial geohazard register	Intermediate geohazard register	Final geohazard register
Geo-engineering	Foundation concept studies	FEED geo-engineering design, 1 or 2 concepts	Detailed geo-engineering design for chosen concept

Table 4. Site data with project engineering design stage

	Concept	FEED	Detailed Design
Geological	Public domain information, literature	Public domain information, literature, Reconnaissance SI data + possibly Detailed SI data	Public domain information, literature, Reconnaissance SI data + Detailed SI data
Geophysical	Public domain data, legacy data, possibly Reconnaissance SI data [1]	Public domain data, legacy data, Reconnaissance SI data + possibly Detailed SI data [1]	Public domain data, legacy data, Reconnaissance SI data + Detailed SI data [1]
Geotechnical	Public domain data, legacy data, possibly Reconnaissance SI data	Public domain data, legacy data, Reconnaissance SI data + possibly Detailed SI data	Public domain data, legacy data, Reconnaissance SI data + Detailed SI data

1 Since geophysical data is often required over the entire development area it can be advantageous to obtain this in a single survey to inform project decision making as early as possible. A 3D survey or 2D survey with dense line spacing may obviate the need for a second geophysical survey.

11 CONCLUSIONS

A ground modelling framework is presented for offshore wind farm development. The intent is that this framework can be referenced by all project stakeholders. Clients can reference this (including geotechnical interpretation) for setting scopes of work. Consultants and Contractors can build and apply ground models according to this framework, and Certifiers can establish industry requirements against this framework. This alignment is expected to improve consistency, quality and efficiency of ground models, which will improve project management of geo-engineering risk and provide geo-engineering optimisation and performance opportunities.

AUTHOR CONTRIBUTION STATEMENT

P. S. Dimmock: Conceptualisation, Methodology, Project administration, Writing – original draft. **Other Authors**.: Conceptualisation, Methodology, Visualisation, Writing – review and editing.

ACKNOWLEDGEMENTS

The authors are grateful to NGI for support to write this paper.

REFERENCES

Dimmock, P.S., Riera, R., Tam, T.A., Boylan, N. (2023). Geohazard or Geo-engineering constraint? In: *SUT OSIG Conference 2023*, London, UK, pp. 2067-2071. https://doi.org/10.3723/LCMM8896

DNV (2021). DNV-RP-C207, Statistical representation of soil data.

Sauvin, G., Vanneste, M., Vardy, M.E., Klinkvort, R.T., Forsberg, C.F. (2019). Machine Learning and Quantitative Ground Models for Improving Offshore Wind Site Characterisation, In: *OTC Conference 2019*, Houston, US. https://doi.org/10.4043/29351-MS

Vardy, M.E., Clare, M.A., Vanneste, M., Forsberg, C.F., Dix, J.K. (2018). Seismic Inversion for Site Characterisation: When, Where and Why Should We Use It? In: *OTC Conference 2018*, Houston, Texas, USA. https://doi.org/10.4043/28730-MS