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

ISBN 978-2-85782-758-0

Engineering Geological Model Strategy: Data Processing & Ground Modelling for Effective Quantitative Seismic Inversion

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ABSTRACT: As offshore wind (OSW) sites globally continue to increase in size (>2GW or 250km2) site characterisation practice requires standardization to drive integration with geotechnical design. The push for increased efficiency requires a plug and play approach once data acquisition campaigns are concluded to rapidly produce geotechnical interpretative reporting and any subsequent design basis. Specifically, the ability to disseminate results to a wide variety of stakeholders using accessible software platforms is required.
We present a holistic workflow that can be used to develop fully integrated ground models and geotechnical interpretative reports for offshore sites. The workflow presented is based on conventional methodologies, with the enhancement of quantitative seismic inversion to predict geotechnical conditions away from as-sampled locations based on geophysical data alone (Dalgaard et al., 2024). Inputs from geophysical interpretation and available geotechnical testing allows a unified set of geological formations, seismostratigraphic units and soil units to be defined. Importantly, the soil units taken forward for the integrated ground model, are those that are geotechnically significant and affect future foundation design. This iterative workflow provides projects with a means of categorizing all incoming data, and investigating any that falls outside of the expected range of results.
Projects need efficient tools to analyse site-wide ground conditions when new data becomes available. The workflow proposed in this paper utilize:
Bentley OpenGround for the management of geotechnical data; Oasys Giraphe for plotting of geotechnical data; IHS Kingdom for the interpretation of subsurface geophysics; ESRI ArcPro for the visualisation geophysical and geotechnical data; and Bentley Leapfrog for 3D geological ground model.
Keywords: GI, Data Processing, EGM, Seismic Inversion

1 INTRODUCTION

The ground model is a tool for management of geological and geotechnical risk on civil infrastructure projects. It encompasses deliverables, outputs and an overall approach for site characterisation projects. The ground model approach has been advocated recently by the SUT Guidance Note (Cook et al. 2022) and it is further developed in the Engineering Geological Model (EGM) Guidance Notes released by IAEG (Baynes and Parry, 2023) Both documents outline the geological and geotechnical features of a site, enabling an assessment of how these conditions interact with the proposed project. The EGM approach outlines the amount of information required depending on the size of the project and the foreseen geotechnical/geological complexities. For offshore windfarm projects it should be recognised that a the maximum level of EGM development (Level 3) is required. Level 3 requires the commissioning of separate geohazard studies, including geological studies and soil structure interaction studies, multistage subsurface investigations, including boreholes in-situ penetration testing and geophysics, and the production of interpretative reporting including possibly 3D visualisation of the models.

Here a workflow is proposed that summarises all these requirements up to the point of producing specific soil structure interactions. In this approach we propose to summarise the output of an EGM in four main documents which are the Geological Ground Model (GGM), the Geotechnical Interpretative Report (GIR), the Integrated Ground Model (IGM) and the Geotechnical Risk Register. Depending on the stage of development of the offshore site a Geotechnical Baseline Report (GBR) should be considered as well, which can be drafted on the outcome of all the previously developed documentation as specified in CIRIA C807 (Davis et al., 2023).

The GGM is a geophysical-led interpretation of the sub-surface conditions, fully integrated with geotechnical units and geological age dating results. The GIR includes the integration and interpretation of the geotechnical in-situ and laboratory data with parameterisation of characteristic values across the investigation based on the results of the GGM, providing designers the adequate level of information to perform foundation and infrastructure design at various levels. The IGM is a 3D representation of the GGM horizons and GIR properties interpolated across the investigation area for the purpose of the EGM. The IGM defines specific geotechnical parameters as individual cells or voxels with uncertainty characteristics. The GBR allows to allocate the risks associated with the ground between different parties, at different stages of the project devlopement as the document needs to be updated as the the project evolves.

Additionally, the EGM will include the results of quantitative seismic inversion to predict geotechnical conditions away from as-sampled locations based on geophysical data alone (Dalgaard et al., 2024, Cox et al., 2024). Geophysical data is being used increasingly routinely to extrapolate geotechnical properties in large offshore wind farm development areas. This provides the tools to expand the data available for the EGM with the potential to improve schedules and cost-effectiveness of engineering and design that rely upon increasing certainty of ground condition risks and opportunities.

The relative emphasis of the ground model and its ability to guide and inform decisions is a key principle of offshore data acquisition for offshore wind sites. The effective use of the EGM will provide significant benefit to aid decision making using an established framework to integrate large volumes of in-situ and sample data, and ultimately provide developers and designers with confidence in their understanding of geological and geotechnical risk.

2 THE WORKFLOW

Due to the size of offshore wind farm sites, effective site characterisation is necessary to define effective engineering solutions. Separate geophysical and geotechnical approaches might lead to ineffective site-wide interpretations and that is why a phased approach similar to what is described in Rattley et al., (2017) is considered necessary. The benefits of this approach become most evident when the requirements of the geotechnical design process are considered as early as possible in the stages of design. The process outlined here is aligned to the one outlined in Rattley et al., (2017) which will ensure adequate opportunities for thorough gap analysis in the investigation planning.

Similar to what is recommended by Baynes and Parry (2023) the EGM here is broken down in a series of subsequent stages that might need to be iterated through in order to achieve the final deliverables, as discussed in the previous section. The cycle is represented in Figure 1.

The stages comprise:

1. Assemble relevant engineering and engineering geological information that are of significance to the site/project. Define and initial conceptual GGM, or re-evaluate the model using information as it becomes available at different development levels
2. Identify key hazards (seabed or sub-surface obstructions, UXO risk), project specific information like infrastructure layout, engineering significance of different geological units and uncertainties related to the initial strategy for offshore data acquisition.
3. Define the requirement for an offshore campaign, either for a geophysical investigation campaign, and in-situ testing campaign or a sampling campaign or a combination of the above. Iteration on this point should consider data gaps for specific areas of the site and/or specific geological units.
4. Manage the offshore campaign, evaluate progress, review preliminary results and potentially instruct changes to the offshore crew as soon as new information becomes available (software: Seekat)

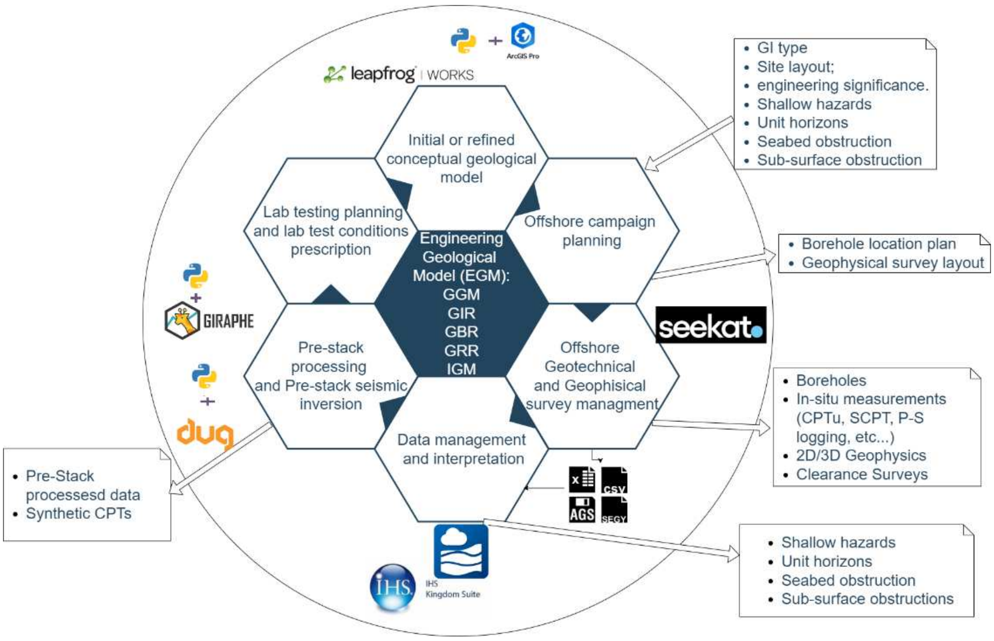

Figure 1 – EGM workflow cycle, together with outputs at different stages and software used

5. Receive the campaign data preferably in industry standard file formats, AGS, SEGY and define your information database (software: OpenGround for Geotech/exploratory information or S&P Kingdom/Dug Insight for geophysical data)
6. Combine the observations and define engineering geological units, and refine the GGM.
7. Characterize the engineering geological units, using standard and advanced laboratory testing . Define advanced lab testing conditions from standard lab characterisation results and the interpretation of in-situ tests. (Software: OpenGround, Oasys Giraphe and custom interpretation tools)
8. Perform pre-stack AVO compliant data processing and Seismic inversion for CPT data prediction. (Software: DUG Insight and custom seismic inversion and predicted CPT tools)
9. From general characterisation of geotechnical parameters and develop the GIR (Software: OpenGround, Oasys Giraphe and custom interpretation tools).
10. Create a 3D IGM, integrating the results of the GGM, the GIR and the CPT predictions derived from seismic inversion (Software: Leapfrog and ArcGIS).
11. Add to the geotechnical risk register any additional hazards, uncertainties, gaps and discrepancies.
12. Evaluate the level of development of the project and, if necessary, undertake additional investigations to improve the knowledge of the site and reduce risk at acceptable levels.

3 DATA MANAGEMENT

As noted in Cook et al, (2022) all data deliverables should be provided in digital format, crucial for enabling effective management and maintenance of the data and to ensure its accessibility both during and after the project. Damage and corruption of physical hard drives especially when not in use, are a concrete risk, and network storage where drives are kept powered on should preferred. Recent cloud storage solutions provide version history functionalities on top normal back-up and might be the method of choice for many current projects, although it generally comes with a maintenance cost to keep the data live. Nonetheless, a project-specific ground investigation data management plan should be created from the outset, to map out how ground investigation data is obtained, reviewed, validated, processed, analysed and transferred between each stage of the geotechnical lifecycle, and the responsible parties involved at each step. The plan should identify industry recognised software if available.

Herein example applications and tools idenfied by the authors, suitable to undertake defined tasks, are shown:

- Innosys Seekat to manage the offshore testing and sampling campaign.
- Bentley OpenGround to store in-situ and lab test data together with exploratory hole information;

- S&P Kingdom for geophysical data interpretation, together with Dug Insight for data processing
- Oasis Giraphe to plot geotechnical data directly from OpenGround database
- Python tools to perform the data processing required to derive engineering properties from in-situ lab test data
- Python tools to perform Seismic inversion to derive, synthetic CPT data from geophysical measurement.

4 THE PROCESSES

This section will further elaborate on the specific use of commercial and custom software to implement the workflow, detailing the processes used to condition the data for pre-stack seismic inversion and the inversion itself, and how these can be utilized in the early stages of project development.

4.1 Geotechnical data management, and Ground investigation planning and management

The data from the different offshore ground investigation campaigns are managed and stored using the commercial software OpenGround. Oasis Giraphe is used to plot most of the geotechnical data, this tool is a web platform that query the data directly from OpenGround server and render the plot in the browser. Additionally, some custom python libraries are used to query the data from OpenGround servers and to perform statistical analysis and plot the data spatially and on a unit by unit basis to aid the identification of data-gaps and to aid the geotechnical interpretation of the data.

Depending on the stage of the ground investigation, the data from the previous campaign will be implemented in the investigation strategy (using the tools just introduced) or the conceptual model will be used to identify an area of particular interest for the investigation. If the scope of a preliminary campaign is to maximise the output of seismic inversion, then SCPTs and P-S logging locations should be placed in an organised way to maximise the coverage to ensure all units are adequately ground truthed for developing synthetic CPTs from geophysical data as introduced below.

4.2 Geophysical interpretation

Seismic interpretation as part of the GGM worksflow is done using S&P Kingdom. The software integrates geophysical, geological, and geotechnical data into a single platform. By interpreting key horizons and features from 2D and 3D seismic data, detailed seismostratigraphic models can be created. The integration of geological and geotechnical data provides ground-truthed information, refining the model further. Outputs from the Kingdom model (Figure 2) are used to build the 3D seismostratigraphic model, forming a structural basis for predicting geotechnical parameters (IGM).

4.3 AVO-compliant pre-stack processing and imaging

Amplitude compliance with offset (AVO) pre-stack data processing is an essential prerequisite to elastic pre-stack inversion, this is performed with the software DUG Insight. To ensure the reliability of the inverted elastic and geotechnical properties, AVO-compliant, pre-stack UHRS processing is required to ensure amplitude preservation of the recorded wavefield (Figure 2), while sufficiently minimising acquisition artefacts which contaminate the amplitude fidelity of the data, such as: swell and cable-related noise, ghost reflections, wavefield directivity, instrumentation statics and free surface multiples.

4.4 Pre-stack inversion and CPT predictions along the geophysical lines

Pre-stack inversion of multichannel seismic data exploits variations in the amplitude of the reflected seismic wavefield with angle of incidence to estimate the elastic properties of the subsurface. The pre-stack methodology provides benefits in schedule acceleration and direct input to geotechnical

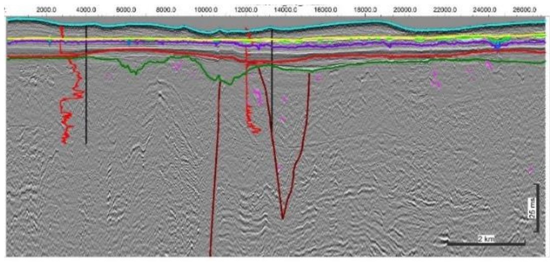

Figure 2 – 2DUHRS section including seismic interpreted reflectors and in-situ CPT traces.

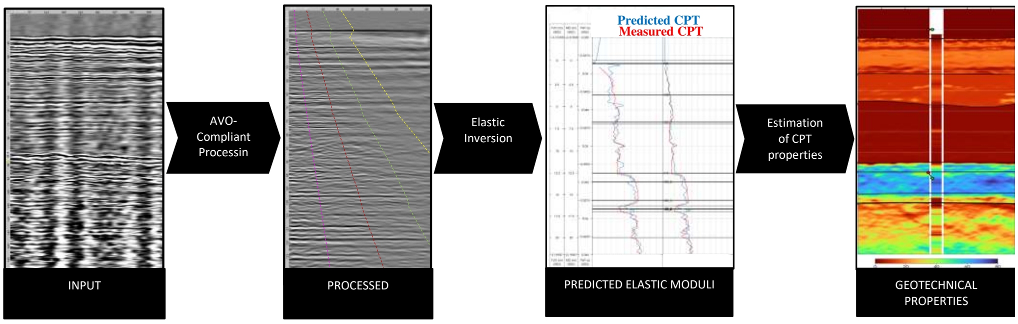

Figure 3 – AVO- compliant processing and pre-stack inversion to predicted CPT example (Cox et al., 2024).

parameterisation and uncertainty derivation for 3D voxel modelling to be performed as part of the IGM.

The methodology that is proposed in this workflow is iterative and is undertaken alongside geophysical processing and conditioning of geophysical and geotechnical data (Figure 3). The geotechnical predictions made are bounded by appropriate measures of uncertainty. Predicted geotechnical measurements can include CPT cone resistance and sleeve friction, pore water pressure – u_2 and Small strain shear modulus - G_{max}.

4.5 3D Geological Model – Leapfrog

A comprehensive 3D model of geological and geotechnical information can be developed using Leapfrog Works. Geological boundaries between seismostratigraphic units, interpreted during the Geological Ground Model (GGM) workflow, are used to construct a 3D seismostratigraphic ground model. This approach ensures data continuity from the GGM to the Integrated Ground Model (IGM) without reinterpreting the geology. Additionally, aseparate 3D geotechnical soil unit model can be created, incorporating geological boundary rasters but grouping certain seismostratigraphic units based on their engineering behaviour. Further to the geological and geotechnical models the Leapfrog project integrates drilling data, Cone Penetration Test (CPT) data, seismic data, and laboratory testing data from various sources, providing developers with a unified environment to review and understand ground conditions. Additionally, the 3D model offers end-users the flexibility to slice it in any direction and at any location, facilitating rapid visualization and better understanding of subsurface conditions.

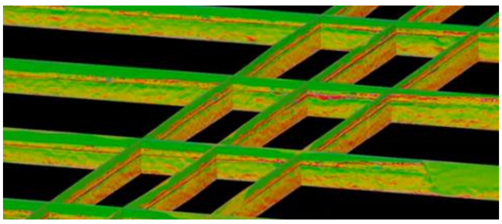

Figure 4 – 3D visualisation of the predicted CPT cone resistance along the seismic lines

4.6 Predicted CPT 3D Interpolation

A full 3D interpolation of the data covering the full site area from the seabed can be performed using ArcGIS pro using the kriging functionalities to generate the continuous voxel model (Figure 6). Kriging produces interpolation uncertainty values, which are combined with the CPT prediction uncertainties to ensure the uncertainty of the prediction is suitably propagated throughout the process. This type of voxel model enables users to select any 20m² location within the site boundary and access a graph of each predicted parameter, including a best prediction value and upper and lower bounds representing the propagated uncertainty.

a)

b)

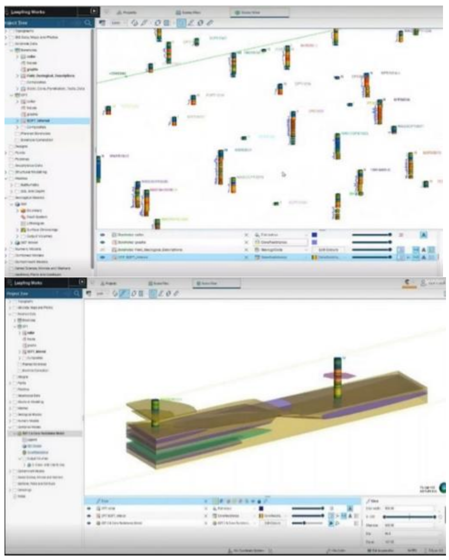

Figure 5 – Leapfrog model ground investigation (a))and 3D geotechnical model (b))

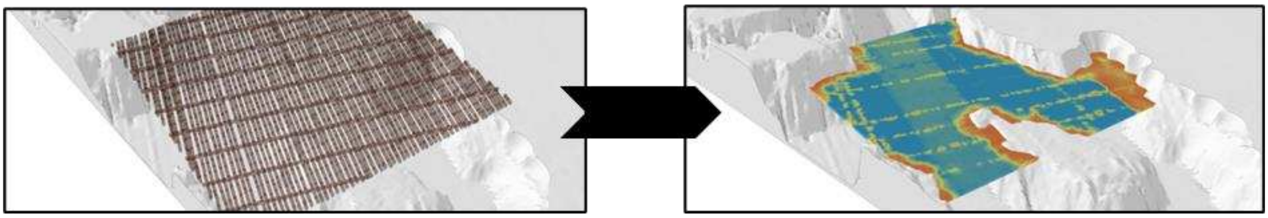

Figure 6 – Seismic lines representation (left) 2D slice of a 3D interpolation of the predicted CPTs properties (right).

Providing these bounds allows the user to perform probabilistic analyses as part of preliminary engineering assessments.

5 CONCLUSIONS

We present a holistic workflow that can be used to develop fully integrated ground models for offshore sites compliant with recognised methodologies like SUT2022 and IAEG, 2023, with the enhancement of quantitative seismic inversion to predict geotechnical conditions away from as-sampled locations based on geophysical data alone. Inputs from geophysical interpretation and available geotechnical testing allows a unified set of geological formations, seismostratigraphic units and soil units to be defined. Importantly, the soil units taken forward for the integrated ground model, are those that are geotechnically significant and affect future foundation design. This iterative workflow provides projects with a means of categorizing all incoming data, and investigating any that falls outside of the expected range of results. Particular emphasis was given to the type and roles of the software used at different stages of the process.

AUTHOR CONTRIBUTION STATEMENT

T. Bizzotto: Inception, Writing- Original draft. **S.Eaton**: Conceptualization, Review. **C.Smith**: Conceptualization, Review. **P.Lipp**: Reviewing and Editing. **P.Cox:** Conceptualization, Methodology, Review. **E.Dalgaard:** Conceptualization, Review. **P. Moran:** Conceptualization, Review. **N. Dakin:** Conceptualization, Review.

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