

# Understanding Ground Conditions



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## *Risks and challenges of offshore wind projects*

### **Who should read this paper?**

Stakeholders interested in the seafloor and sub-seafloor conditions across proposed wind energy development areas and how they impact the location, installation, and design of project facilities (i.e., turbines, sub-stations, cables) will find this paper of value. This will include energy regulators, data acquisition companies, offshore wind developers, local communities, and other marine industries (e.g., shipping, fishing, tourism).

### **Why is it important?**

There is a large body of public domain literature and data on the ground conditions offshore Nova Scotia, most of which has been generated by the Geologic Survey of Canada. This paper integrates this information in the context of offshore wind development and summarizes the ground-related risks and uncertainties that face future offshore wind projects. It draws on industry-leading expertise in geological and geotechnical site characterization, and specifically from key players in successful offshore wind projects around the globe. Two of these projects are presented as case studies, providing an expectation of things to come and a basis to predict potential future complications, plan for process improvements, and generate efficiencies.

Nova Scotia is poised for a rapid transition in energy supply and much of its generation capacity lies off the Atlantic coast where conditions are right for large-scale offshore wind development. As outlined in its roadmap for offshore wind development, including the Wind West project, the next decade will see a significant increase in ocean activities. This will include metocean surveying, marine site investigation, and port developments, but this is all predicated on the technical and commercial success of the first few projects. This success will require a tremendous degree of collaboration and aligned effort across all stakeholders, and this paper could help develop the necessary line of sight.

Much of this paper builds from a Desktop Study that was completed in August 2025 (and updated in November 2025), the lead for which is also the lead author in this paper. The study – both a full report and a digital project – is available at <https://info.tgs.com/nova-scotia-desktop-study>.

### **About the authors**

Dr. Trevor King is lead principal geoscientist at NGI with over 25 years of experience in technical, project management, and strategic planning roles that span the range of geologic settings and operational environments. Recent work has included the integrated interpretation of geoscience and geotechnical data to generate ground models in the Americas and Europe, the development of machine learning algorithms to estimate glauconite content in soils, and leading a desktop study to understand wind and ground conditions offshore Nova Scotia. Prior to NGI he worked for Vår Energi, Imperial Oil, and ExxonMobil on offshore projects across the globe, living in Canada, UK, Norway, Nigeria, and USA. He is a technical expert in seismic interpretation, site characterization, data science, and geographical information systems.

Dr. Luke Griffiths is a senior geophysicist at NGI specializing in geophysics, subsurface characterization, inversion, and data science. With a PhD in experimental geophysics and extensive experience in both laboratory and field studies, he leads and contributes to ground model development projects integrating geological, geophysical, and geotechnical data for major offshore wind developments. His skills in numerical analysis, inverse methods, and data science allow him to process, integrate, and present complex and heterogeneous geoscientific datasets to provide new and robust understanding of challenging geological environments. He has served as geoscience lead on large offshore wind projects, including Arklow Bank Wind Farm and Bałtyk II and III, has authored over 20 peer-reviewed publications and conference proceedings, and is a regular reviewer for international journals in geophysics.

Dr. Maarten Vanneste is a technical expert at NGI with more than 25 years of experience from both academia and consultancy. At NGI since 2006, his work includes offshore geohazard and risk assessment, integrated site characterization, geophysical mapping techniques, multi-component seismics, quantitative seismic interpretation, fluid flow phenomena, and the development of data-driven ground models with particular focus on offshore renewables. He is a leading member of the ISO Technical Panel 19901-10 on Marine Geophysical Investigations; chairman of the bi-annual conference series Applied Shallow Marine Geophysics, initiated in 2014, under the umbrella of the EAGE Near-Surface Geoscience Division; and Scientific Committee member of the EAGE Energy Transition Conferences. He has overseen and guided most of the integration and geoscience activities for various large offshore wind projects (e.g., Empire Wind, Dogger Bank South, Bałtyk II and III, Arklow Bank, Ten noorden van de Waddeneilanden, IJmuiden Ver, Mona, Morgan, Morven), and has authored or co-authored over 50 peer-reviewed publications and conference proceedings.

## OFFSHORE WIND SITE CHARACTERIZATION: EXAMPLES FROM NOVA SCOTIA, AMERICA, AND EUROPE

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### ABSTRACT

The technical and commercial success of offshore wind farms requires a robust understanding of ground conditions so that facilities can be optimally located and designed, and then successfully installed and operated. At the outset, a desktop study can provide an initial assessment of the ground conditions (i.e., geohazards, engineering constraints, and soil/rock properties) that are expected across potential project sites. This can aid screening-level decisions around project feasibility and concept selection and, where outcomes are positive, additional site investigation data are acquired. An understanding of the spatial variability in ground conditions is then developed as a ground model. As a project matures toward final investment and uncertainties are further reduced, the ground model can become increasingly quantitative and may include probabilistic predictions of properties in 3D.

This paper summarizes the ground-related risks and challenges that offshore wind projects will face in Nova Scotia, many of which result from glacial processes that were active over ten thousand years ago. We discuss how to maximize the value of new geophysical, geotechnical, and geological data and illustrate the importance of collaboration across these technical disciplines. Case studies from developments in formerly glaciated regions demonstrate how robust site characterization can optimize engineering decisions and reduce development timeframes. We conclude with a look to the future and suggest steps that may help Nova Scotia realize its bold offshore wind vision.

**Keywords:** Nova Scotia, offshore wind, site investigation, site characterization, desktop study, ground model, geohazards, engineering constraints, geotechnical properties, seismic inversion, machine learning, value of information

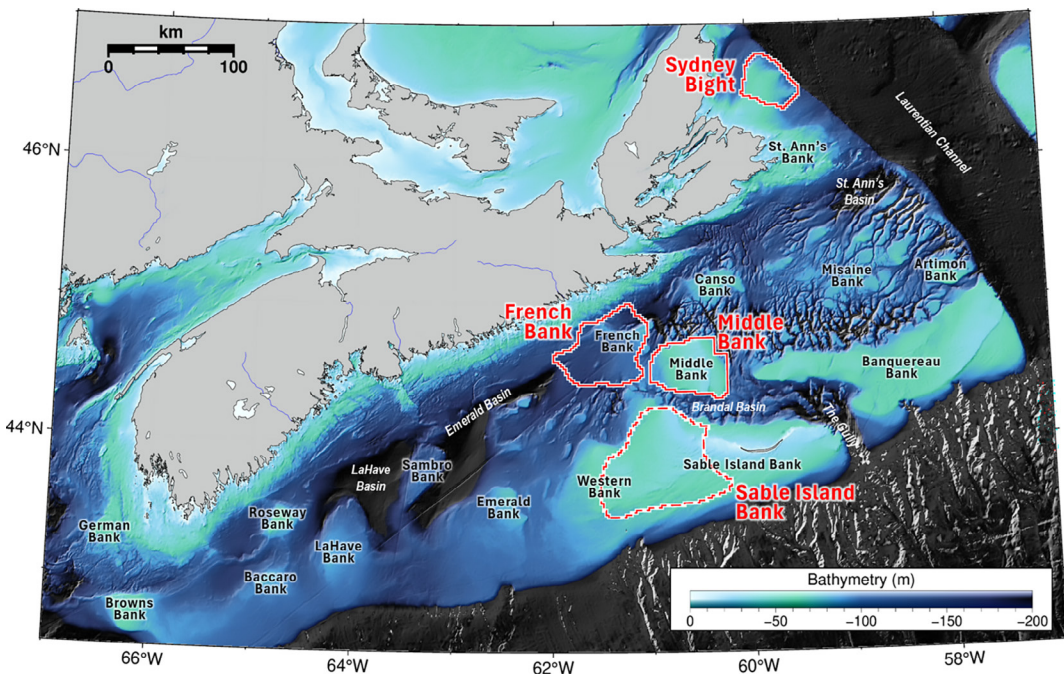


Figure 1: Bathymetry map (colour bar clipped to 200 m water depth; data from [2]), showing the shallower banks (black labels) and deeper basins (white labels) across the continental shelf. Solid red polygons show the three Wind Energy Areas (WEAs) that will be the focus of Nova Scotia's first offshore wind licensing round; Sable Island Bank WEA is expected to be included in future rounds.

## 1. INTRODUCTION

Nova Scotia is preparing for the large-scale development of its significant offshore wind resource. This will initially focus on three of four designated Wind Energy Areas (WEAs; Figure 1) – French Bank, Middle Bank, Sydney Bight – which cover a combined area of 6,700 km<sup>2</sup>, and where water depths range between 30 and 220 m. At anticipated nacelle elevations, mean annual wind speeds exceed 9.5 m/s [1], which is more than sufficient for commercial-scale development. Licensing activities are under way and the expectation is that several parcels across the three WEAs will be available for bidding in a first round that will conclude in 2026.

By 2030, the province is aiming to have wind farm licenses in place for 5 Gigawatts (GW) of generation capacity, and successful bids from the 2026 round may account for up to 3 GW of this. For 15 Megawatt (MW) Offshore Wind

Turbines (OWTs) spaced at 1 nautical mile, 3 GW requires around 200 OWTs spread across 685 km<sup>2</sup>. This represents ~10% of the area within the three WEAs. While commercial-scale offshore wind farms can range in size, Nova Scotia is expecting the first licensing round to initiate three or four projects.

This represents the beginnings of the larger Wind West Atlantic Energy project that plans for 15 GW of operational capacity by 2040 [3], [4]. This may require the installation of around 1,000 turbines over the next ~15 years covering over 3,000 km<sup>2</sup> of the banks and basins shown in Figure 1. The Wind West project sees an ultimate potential of over 60 GW of generation capacity in Nova Scotia.

Offshore wind development at this pace, which historically has only been sustained and exceeded in China, is predicated on the assumption that Nova Scotia's initial projects demonstrate both technical feasibility and

commercial viability [5]. A critical factor for this is the presence of safe and stable ground conditions that can support a range of project facilities, including fixed-bottom turbine foundations, floating turbine anchors, and power cables both within licenced areas and for export to shore.

This paper uses some of the Desktop Study (DTS) results from [1], which includes in-depth discussion on the wind conditions and shallow geology offshore Nova Scotia. The study goes on to describe ground conditions, maps their variability across the offshore region, and quantifies their impacts on development concepts within each WEA.

## 2. NOVA SCOTIA GEOLOGIC SETTING

### 2.1 Glaciation

Offshore wind farm planning typically requires an understanding of the upper 50 to 100 m of the seabed. For example, some of the deepest OWT foundations to date were installed offshore Scotland at the 1.1 GW Seagreen wind farm that penetrate up to 59 m below the seafloor [6]. Across the Nova Scotian shelf, the shallow geology is heavily influenced by Quaternary glaciation, especially the most recent Wisconsinan phase that lasted from around 75 to 11 thousand years (kyr) ago.

At its maximum extent around 20 kyr ago – the so-called Last Glacial Maximum (LGM) – the Laurentide Ice Sheet covered all of Nova Scotia and extended as far out as the current shelf-slope break [7]. Fast-flowing ice streams within the sheet carved deep channels that persist today as distinct bathymetric features,

including “The Gulley” between the Sable Island Bank and Banquereau Bank and the U-shaped Laurentian Channel between Nova Scotia and Newfoundland (Figure 1). Thick sequences of mounded till were deposited in terminal moraines across the outer Scotian Shelf (Figure 2).

Complex patterns of sediment deposition and erosion occurred across Nova Scotia as the ice sheet cycled through periods of advancement and retreat that, combined with sea level fluctuations, generated significant geologic heterogeneity. This includes glacial till and boulders from sub-glacial and moraine deposition, glacial outwash sands and muds from meltwater streams, mud and silt from meltwater plumes outboard of the ice sheet, and dropstone boulders. In beach and subtidal areas, deposits were reworked into cleaner sands. Additional complexity results from tunnel valleys formed by sub-glacial streams of high-pressure water, glaciotectonic deformation within grounding zones (e.g., push moraines), and freeze-thaw weathering.

Nova Scotia has been ice-free for the last 10 kyr and the shelf became progressively submerged as sea level rose through the Holocene. Today, only Sable Island remains above the waves (Figure 3) and the last remnants of the great Laurentide Ice Sheet are seen as ice caps over 2,000 km away in Nunavut.

### 2.2 Shallow Geology

The Geological Survey of Canada (GSC) has undertaken numerous studies across the areas being considered for offshore wind development (e.g., [9], [10], [11], [12], [13]).

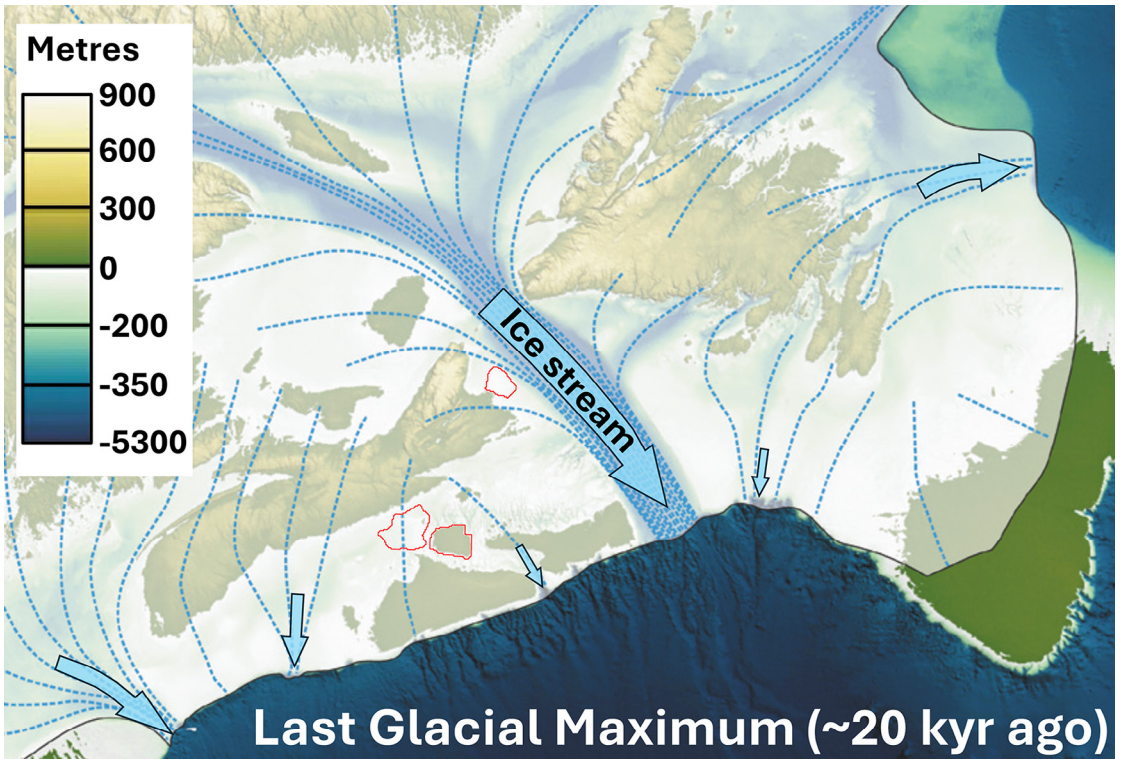


Figure 2: The extent of the Laurentide Ice Sheet at the Last Glacial Maximum (modified from [7]). Colour bar represents ground elevation 20 kyr ago, dashed blue lines are generalized ice flow lines, and blue arrows indicate major ice streams. Red polygons show the four designated Wind Energy Areas (WEAs).



Figure 3: Aerial photograph of Sable Island [8]. The crescent-shaped island is about 40 km long and 1 km wide, with sand dunes up to 30 m high.

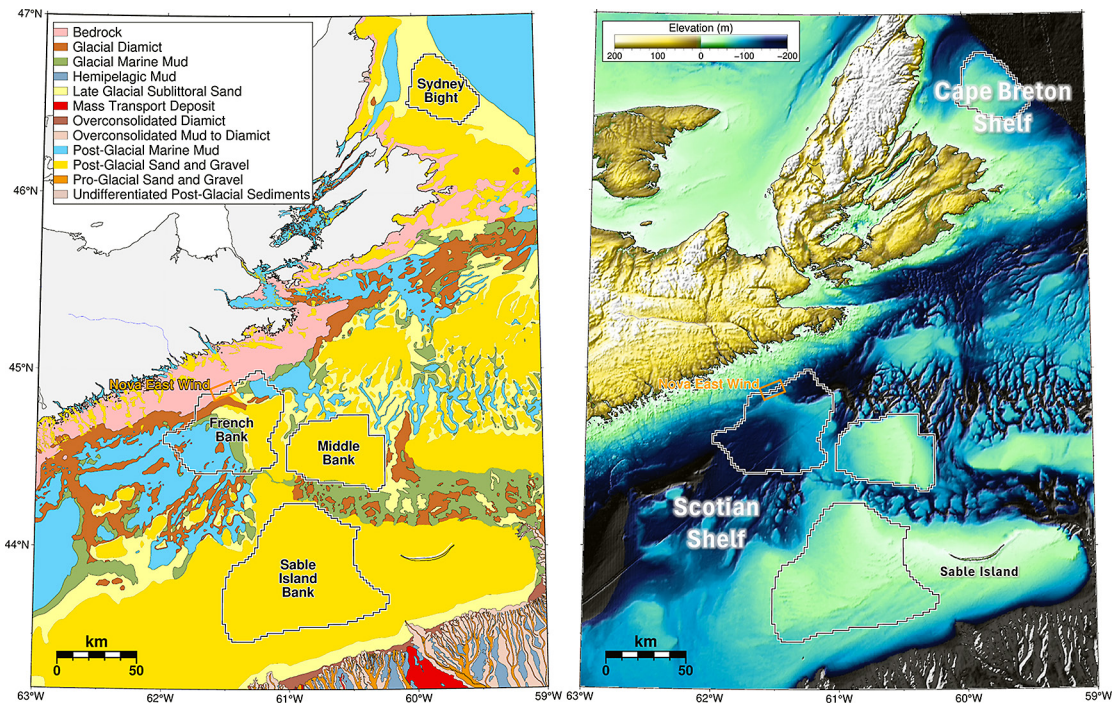


Figure 4: Seafloor geology (left [12]) and bathymetry (right [2]). Black polygons show the designated Wind Energy Areas (WEAs), of which three are on the Scotian Shelf (French Bank, Middle Bank, Sable Island Bank) and one on the Cape Breton Shelf (Sydney Bight). Orange polygon shows the approximate location of a planned floating wind development called Nova East Wind [14].

Table 1: Seafloor lithologies across the shelf (adapted from [9], [11], [12]). Lithology column colours correspond to those across shelfal areas in Figure 4. “Glacial” and “Post-glacial” refer to the Wisconsinan glaciation event.

Lithology	Description	Depositional environment
Post-glacial	Sand & gravel	Sand with gravel; often with mobile bedforms, coarse lags & boulders
	Mud	Soft clay & silty clay; weakly stratified, with some organic layers and fine sand
Glacial	Sand	Muddy sand, fine sand & silt; little gravel
	Mud	Silty clay with dropstones; stratified, with varying amounts of sand & gravel
	Till	Poorly sorted conglomerates of boulders, gravel, sand & mud (i.e., diamict)
Bedrock	Various	Variable lithologies e.g., Cambro-Ordovician metamorphics, Devonian granites, Carboniferous clastics & coals, Mesozoic-Cenozoic (pre-Wisconsinan) clastics

Based on its studies, the seafloor geology can be grouped into post-glacial, glacial, and bedrock lithologies (Figure 4; Table 1). Across the entirety of two WEAs (Middle Bank, Sydney Bight), “post-glacial sand and gravel” is exposed at the seafloor, whereas the

seafloor geology across the French Bank WEA is more variable and all of the lithologies described in Table 1 are present.

Currently, limited information is available on the sub-seafloor geology within the WEAs.

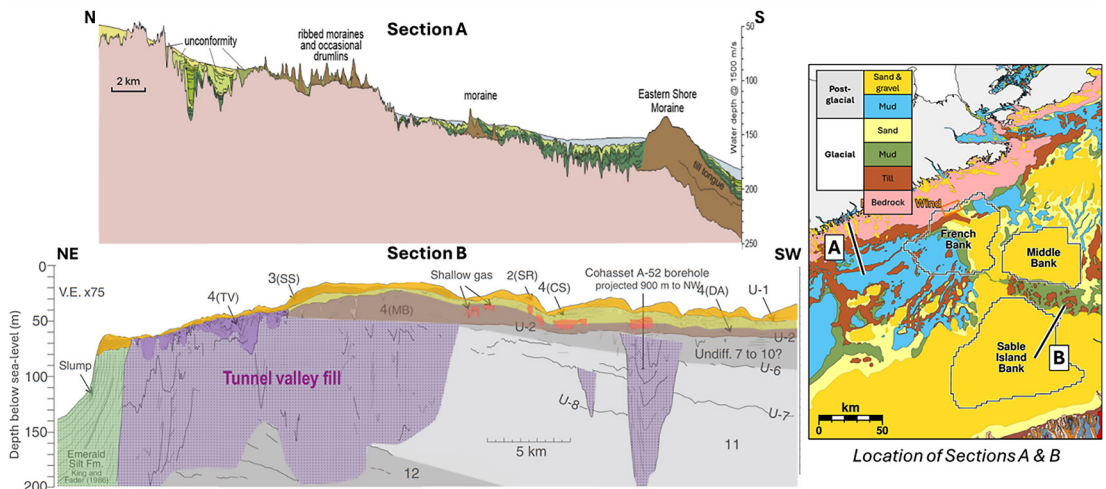


Figure 5: Two published cross sections [10], [21], locations shown on geologic map (modified from [12]). Sections are shown at the same vertical and horizontal scale, with a vertical exaggeration of 75.

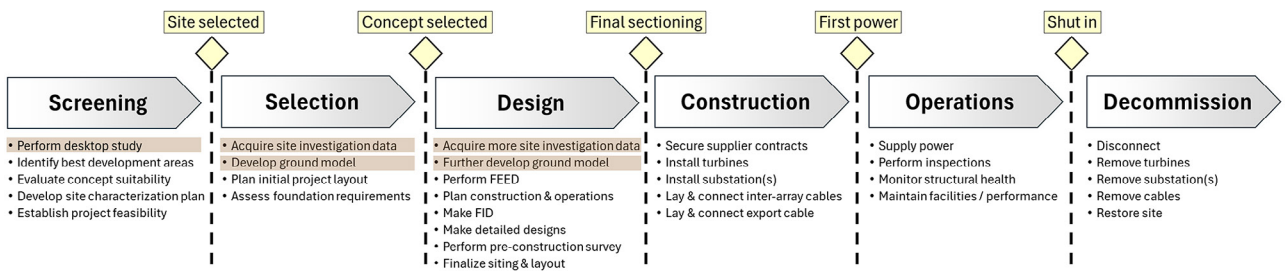


Figure 6: General offshore wind project cycle, with decision gates (yellow) separating development stages. Lists show typical activities, brown shading indicates those for site characterization. FEED: front-end engineering design. FID: final investment decision.

From a general understanding of glacial processes (e.g., [15], [16], [17], [18], [19], [20]), we expect a complex layering and interfingering of glacial and post-glacial lithologies with rapid variations in thickness. This is supported by published seismic cross sections and their interpretations (e.g., Figure 5).

### 3. SITE CHARACTERIZATION

#### 3.1 General Workflow

A generalized offshore wind project development workflow is shown in Figure 6, where capital and risk are managed through a series of stages separated by decision gates.

Site characterization aims to understand the ground conditions across a development area,

which can be grouped into three broad categories:

- **Geohazards:** dynamic or geologic processes that risk project safety and integrity e.g., mobile bedforms, slope instability, earthquakes
- **Engineering Constraints:** static features that impact facility location and design e.g., anomalously soft soils, boulders, existing infrastructure
- **Properties:** geologic and geotechnical parameters e.g., lithology, density, shear strength

At the outset, a DTS of publicly available data can provide an understanding of the ground conditions to facilitate Screening decisions such as project feasibility, site selection, and

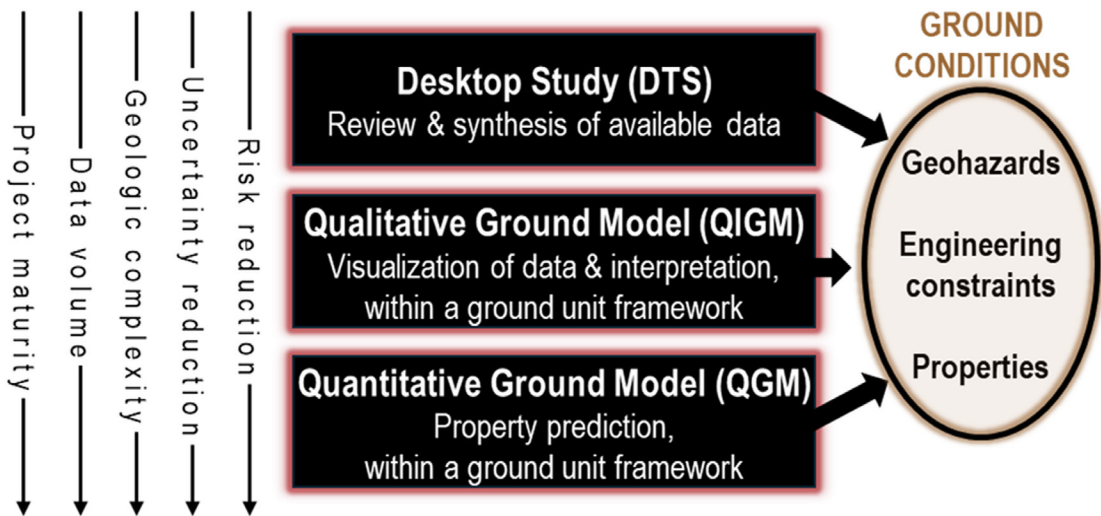


Figure 7: Ground model level of detail, generally increasing from Desktop Study (DTS) to Qualitative Ground Model (QIGM) to Quantitative Ground Model (QGM). More detail may be necessary for higher ground complexities and later project decisions. (Ground unit framework is discussed in Section 3.3.)

the suitability of specific foundation concepts. Where outcomes are positive, additional data are acquired and interpreted, and the spatial variability in ground conditions is represented as a ground model. Several phases of site investigation and ground model generation can occur through the project Selection and Design stages (Figure 6).

We note that while this workflow is generally applicable, different regulatory bodies may award project licenses at different stages. For example, the US Bureau of Ocean Energy Management (BOEM) has held licensing rounds during the Screening stage (e.g., Section 4.1), and the Netherlands Enterprise Agency (RVO) holds licensing rounds in the Design stage (e.g., Section 4.2).

The level of detail in a ground model increases with project maturity as more data are acquired and should ultimately scale with geologic complexity. Where this complexity is modest, a Qualitative Ground Model (QIGM) based on widely spaced data may be adequate for project development. For areas of higher complexity, a

Quantitative Ground Model (QGM) based on large volumes of high-resolution data may be necessary to reduce uncertainties and risks to acceptable levels (Figure 7).

Whether due to local regulations or final design requirements, a Cone Penetration Test (CPT), Borehole (BH), or Vibrocore (VC) may ultimately be acquired at most (and maybe all) foundation locations. While this may cause some to speculate “*if we’re going to measure properties, why model them?*”, the following value propositions should be considered:

- **DTS:** An early and accurate understanding of the expected ground conditions and their levels of complexity can generate significant efficiencies by enabling robust decisions around project feasibility, licensing strategy, and initial site investigation.
- **QIGM:** Where ground complexity is modest, qualitative models showing the geologic and geotechnical variability across a site may be sufficient to proceed

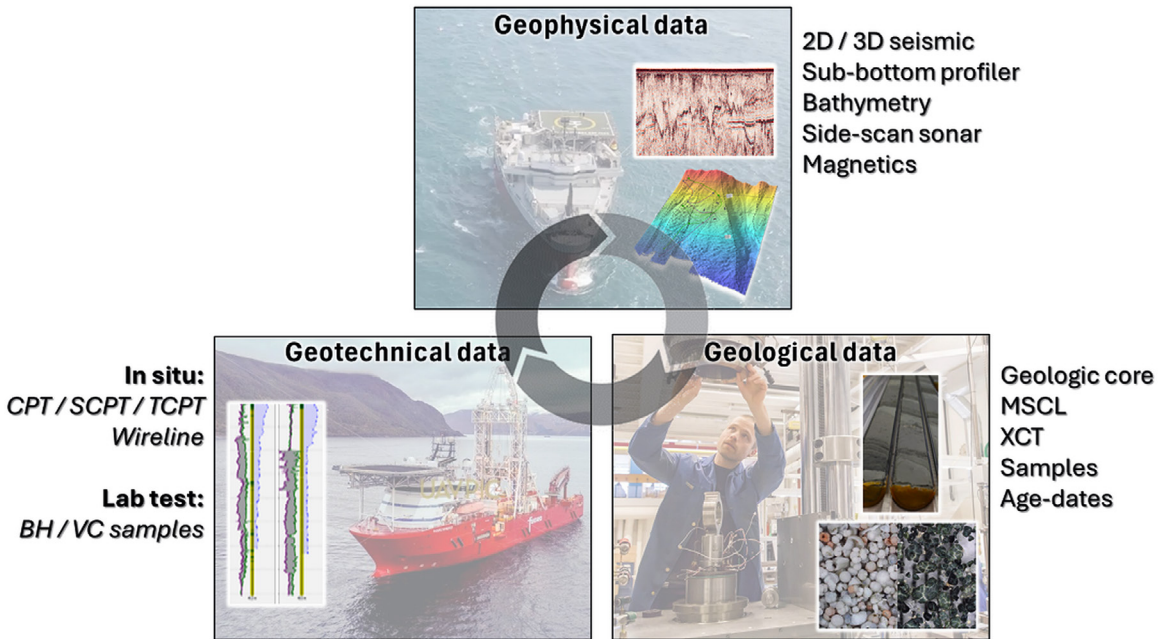


Figure 8: Site investigation data typically required to understand ground conditions across an offshore wind site. CPT: Cone Penetration Test. SCPT: Seismic CPT. TCPT: Thermal CPT. BH: Borehole. VC: Vibrocore. MSCL: Multi-Sensor Core Logging. XCT: X-ray Computed Tomography.

to the Construction and Operations stages. In more heterogeneous regions, the model can identify areas of high complexity and critical uncertainty that require further investigation.

- QGM:** The ability to predict geotechnical properties (and their uncertainties) at any location across a site can provide flexibility and guard against unforeseen complications, especially in areas of high geologic complexity. If the geotechnical data at a planned foundation location is poor (e.g., early refusal, low recovery) or absent (e.g., only one CPT acquired across several floating anchor locations), a predictive model may provide a design basis with the required level of confidence. In addition, where there is some uncertainty in the final deployed location (e.g., anchors, torpedo piles), a predictive model may identify large enough target areas where geotechnical variability

remains within tolerance limits. If a foundation location needs to be optimized (i.e., micro-siting) or changed (e.g., clearance requirement, installation failure), a location that is further from geotechnical measurement may be selected on the basis of predicted parameters.

Ultimately, the value of a ground model is measured by its ability to reduce uncertainties and risks to levels that enable the project to progress to the Construction and Operations stages in an efficient and cost-effective manner. This is returned to in the case studies presented in Section 4.

### 3.2 Site Investigation

Several types of data are required to understand ground conditions for a project to develop and operate successfully. These generally fall into three categories: geophysical, geotechnical, and geological

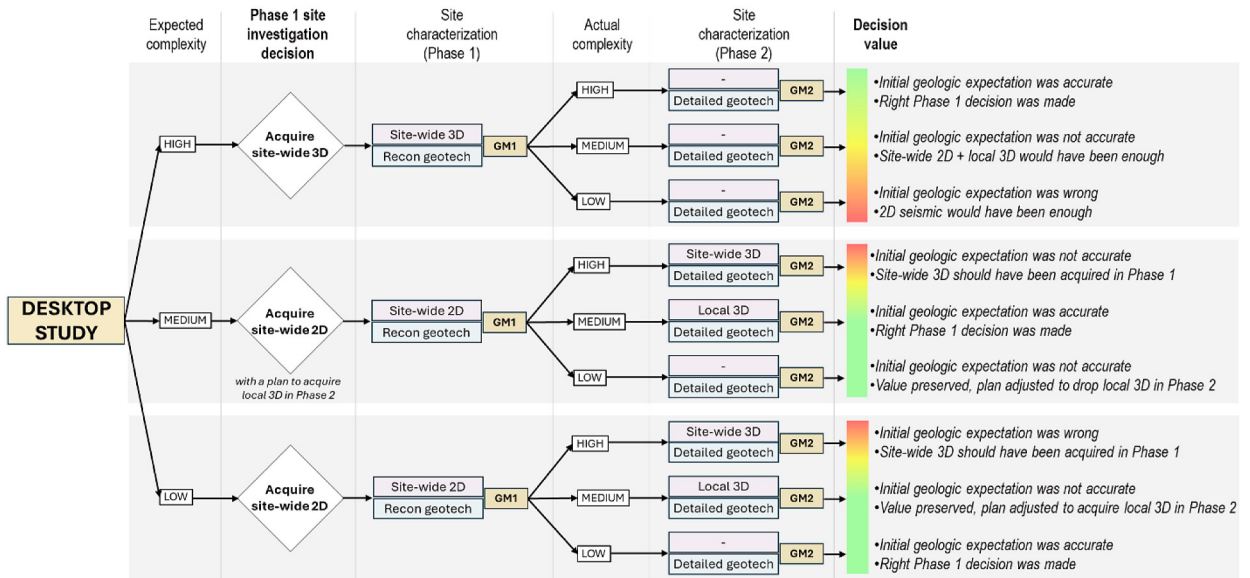


Figure 9: Value creation (green) or erosion (red) related to the decision to acquire site-wide 2D or 3D seismic data early in site characterization. Assumes “low” geologic complexity is adequately resolved on 2D, “medium” complexity requires some local 3D, and “high” complexity requires site-wide 3D seismic. GM1 and GM2 refer to ground model iterations.

(Figure 8). Maximizing the value of these data requires coordinated acquisition plans that continually refer to the evolving ground model to target the reduction of project-critical uncertainties.

### 3.2.1 Geophysical Data

Ultra High-Resolution (UHR) or extremely high-resolution multi-channel seismic reflection data [22] are probably the most important geophysical data for accurate characterization of offshore wind sites. The higher the frequency content, the higher the resolution, although there is a natural trade-off with imaged depth as higher frequencies are preferentially attenuated. In general, sub-metre vertical resolution to depths of at least 50 m is desired.

Deciding whether, where, and when to acquire 3D seismic should consider the value of information given the expected level of geologic complexity (although additional

factors may be important [23]). Early and site-wide 3D seismic may add value in highly complex areas, enabling the migration of energy to its true point of reflection and allowing detailed geologic mapping. Alternatively, where geology is less complex, it may be better to acquire site-wide 2D seismic, and later – when ground conditions are better understood – acquire 3D in areas of highest uncertainty and risk (e.g., [24]). Figure 9 illustrates how a good and reliable DTS can be a significant factor in making the right decision.

Understanding the seafloor and the first few metres of the seabed often requires the acquisition of additional geophysical data such as Sub-Bottom Profiler (SBP), Multibeam Echosounder (MBES) bathymetry, Side Scan Sonar (SSS), and Magnetics (MAG). These data are typically acquired along with high-resolution seismic (Figure 10; [25]), and integrated interpretations are critical to

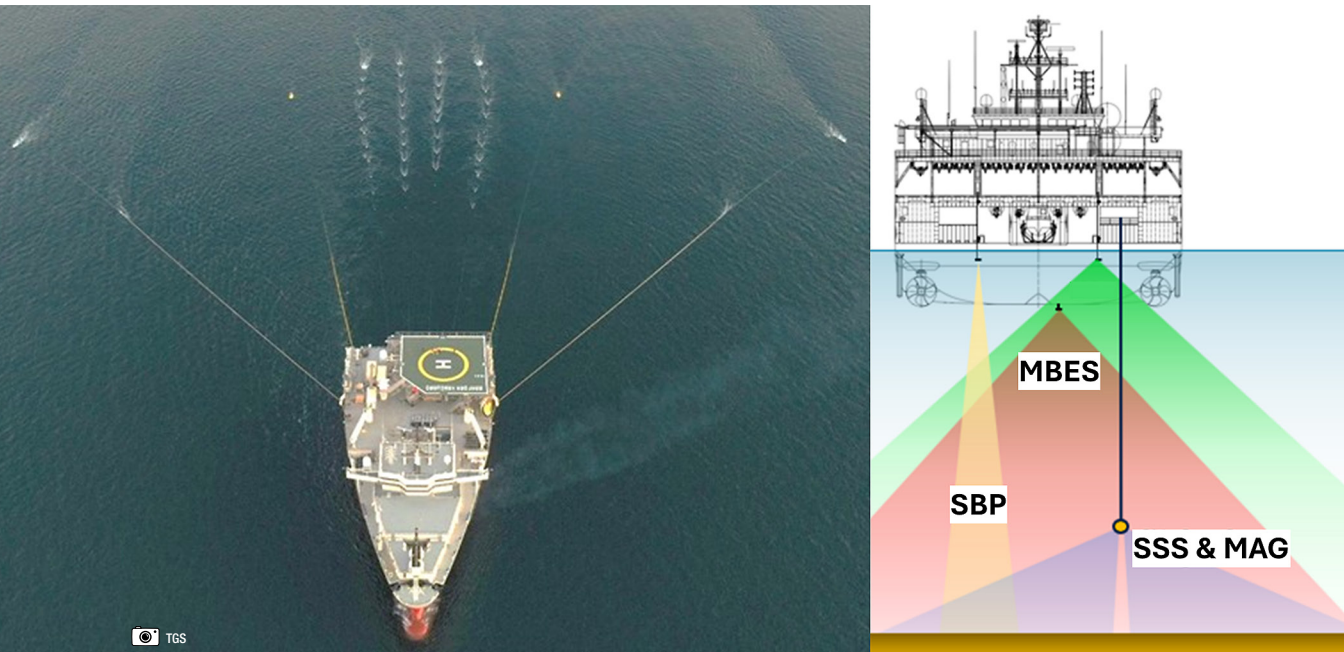


Figure 10: Integrated acquisition of Ultra High-Resolution (UHR) seismic and other geophysical data. MBES=Multibeam Echosounder. SBP=Sub-Bottom Profiler. SSS=Side Scan Sonar. MAG=Magnetics.

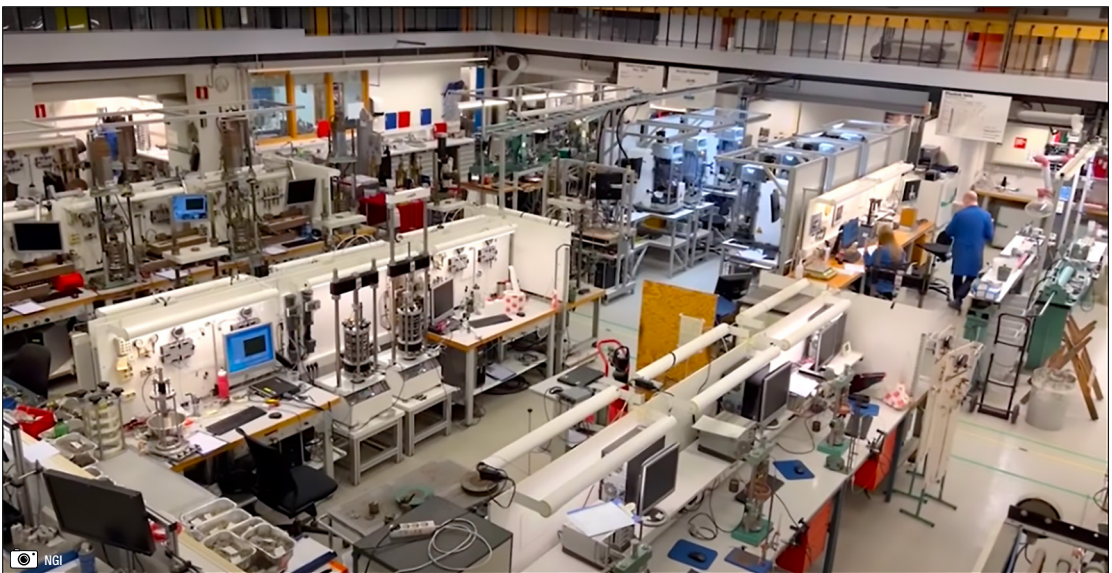


Figure 11: Geotechnical laboratory testing.

accurately identify, characterize, and map geohazards and engineering constraints in the ground model.

### 3.2.2 Geotechnical Data

Geotechnical data are obtained through CPTs,

BHs, VCs, and wireline log measurements. Subsequent analyses, including basic and advanced laboratory testing (Figure 11), generate depth profiles of the geotechnical properties that are critical to engineering design and installation. These properties are

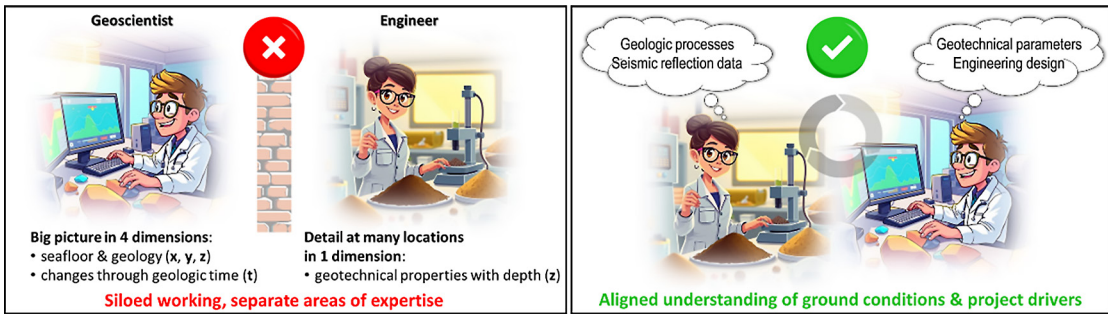


Figure 12: Effective integration of geoscience and engineering expertise requires mutual understanding of disciplines with an aligned view of ground conditions and project drivers.

expected to vary significantly across formerly glaciated regions. As site characterization progresses, it is typical to see multiple site investigation campaigns e.g., an initial “reconnaissance” phase followed by “detailed” phases that target critical uncertainties identified in the evolving ground model (see Figure 9). In general, locating geotechnical data precisely on seismic lines can reduce uncertainty in their integrated interpretation and generate more accurate ground models.

### 3.2.3 Geological Data

Geological data come from tests performed on samples obtained from the seafloor, BHs, and VCs. The most fundamental of these is a core description – often integrating high-resolution photography, Multi-Sensor Core Logging (MSCL), X-ray Computed Tomography (XCT), CPT, and wireline data – to describe the vertical succession of geologic facies at a single location. This includes grain types, grain sizes, sedimentary features and fossil assemblages and, when integrated with seismic/SBP data, can help understand the lithologic variability across a site. This is often enhanced by performing radiocarbon and biostratigraphic age-dating at key locations and depths to understand the depositional history across the

project site and establish a robust, chronostratigraphic ground unit framework.

### 3.3 Ground Model Generation

Overly conservative engineering of offshore wind structures is undesirable, and accurate ground models are needed to generate optimal and lowest-cost geotechnical designs. This begins with the interpretation of a 3D “ground unit framework” (sometimes called a “structural framework,” “stratigraphic framework,” or “geologic ground model”), a succession of chronostratigraphic layers whose boundaries correspond to seismic reflection events (i.e., “horizons”) and to measured changes in geotechnical/geological properties. The spatial variability in the properties of a single unit may then be understood by considering the distribution of environments and processes that were present during (and maybe also following) its deposition.

Seismic interpretation is typically performed in the Two-Way Time (TWT) domain and tying ground unit boundaries to geotechnical data generates interval velocities. These can be used in conjunction with other velocity information (e.g., seismic, wireline, Seismic Core Penetration Test (SCPT), MSCL) to generate a ground unit framework in depth.

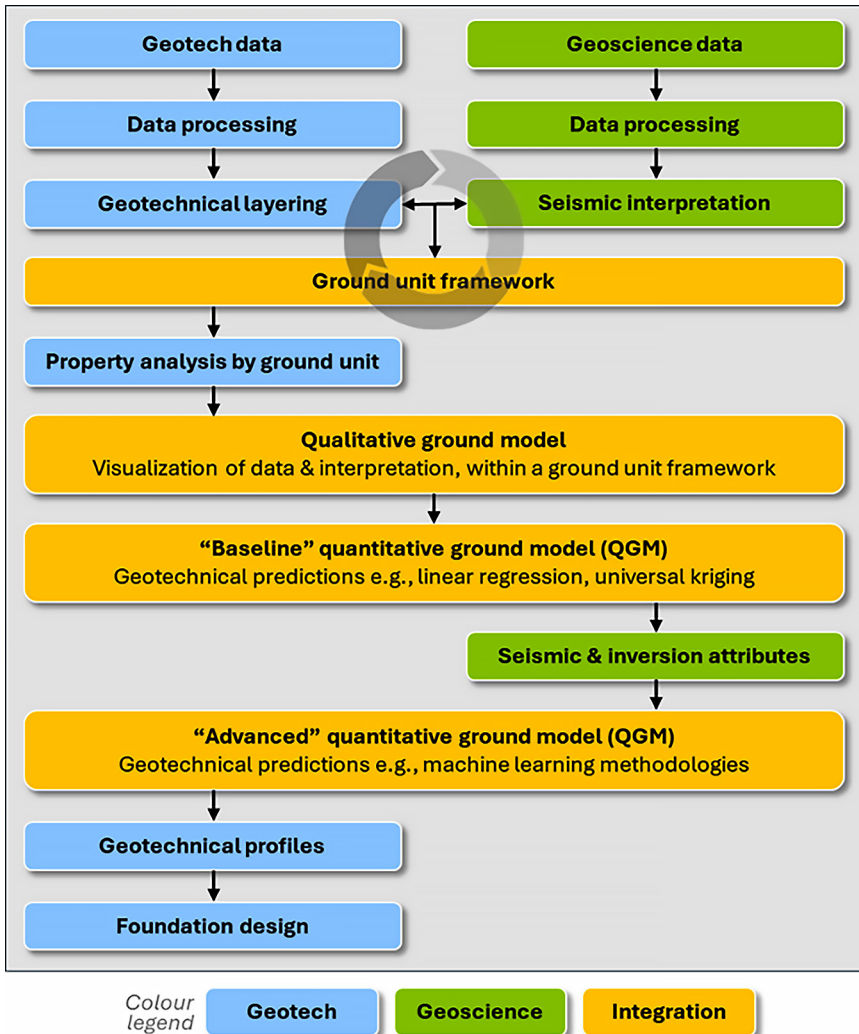


Figure 13: General workflow for qualitative and quantitative ground models. After site investigation data have been acquired and processed, geoscientists and geotechnical engineers define and map a ground unit framework in 3D. Geotechnical measurements are then analysed, understood, and – if required – predicted across a project site within that framework.

As more data are acquired, it is often necessary to update this framework – such as adding/sub-dividing units and refining their top and base depths – requiring close collaboration between geoscientists and geotechnical engineers (Figure 12).

As a project matures toward the Construction and Operations stages, more targeted data are acquired to address critical uncertainties and the level of detail in the ground model

increases (see Figure 7). Ground models may become more quantitative and include probabilistic prediction of properties in 3D (Figure 13). The simplest predictions involve linear regression and geostatistical interpolation to predict properties within each ground unit. If combinations of seismic and inversion attributes are shown to correlate with geotechnical measurements, then machine learning techniques can be used to make predictions [26].

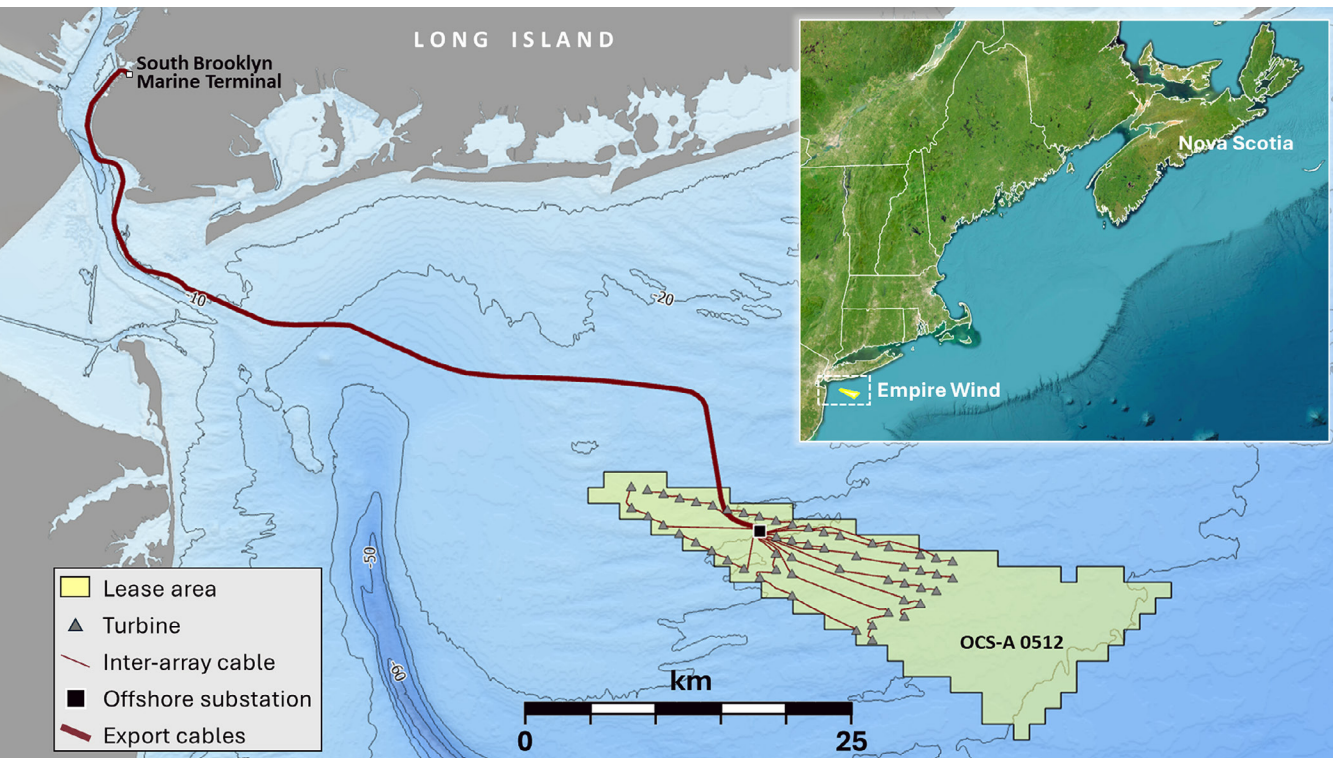


Figure 14: Empire Wind location map. The project includes 54 turbines in water depths of 23-36 m, and 150 km of export cable connecting the substation to the South Brooklyn Marine Terminal.

## 4. CASE STUDIES

The approach described in the previous section is being followed at offshore wind projects in formerly glaciated regions including the US Atlantic, the North Sea, the Irish Sea, the Barents Sea, and the Baltic Sea. We highlight two case studies where ground conditions are analogous to those present offshore Nova Scotia: Empire Wind (USA) and Ijmuiden Ver (IJV; Netherlands).

### 4.1 Empire Wind, USA

#### 4.1.1 Project Summary

Empire Wind is located in the New York Bight about 30 km south of Long Island, where water depths range between 23 and 36 m (Figure 14). The 320 km<sup>2</sup> offshore lease

area (OCS-A 0512) was awarded to Statoil (now Equinor) in a December 2016 licensing round. Site investigation began in 2018 with BOEM's approval of the site investigation plan, and the final Construction and Operations Plan was approved in February 2024. The development includes 54 OWTs (15 MW capacity) on monopile foundations for a total project capacity of 810 MW. Over 150 km of inter-array cables will connect these to an offshore substation, and two 75 km long export cables will connect to a terminal in south Brooklyn at the western tip of Long Island. Front-End Engineering Design (FEED) commenced in February 2021, construction began in April 2024, monopile installation began in September 2025, and first power is expected by the end of 2026, ten years after the licensing round.

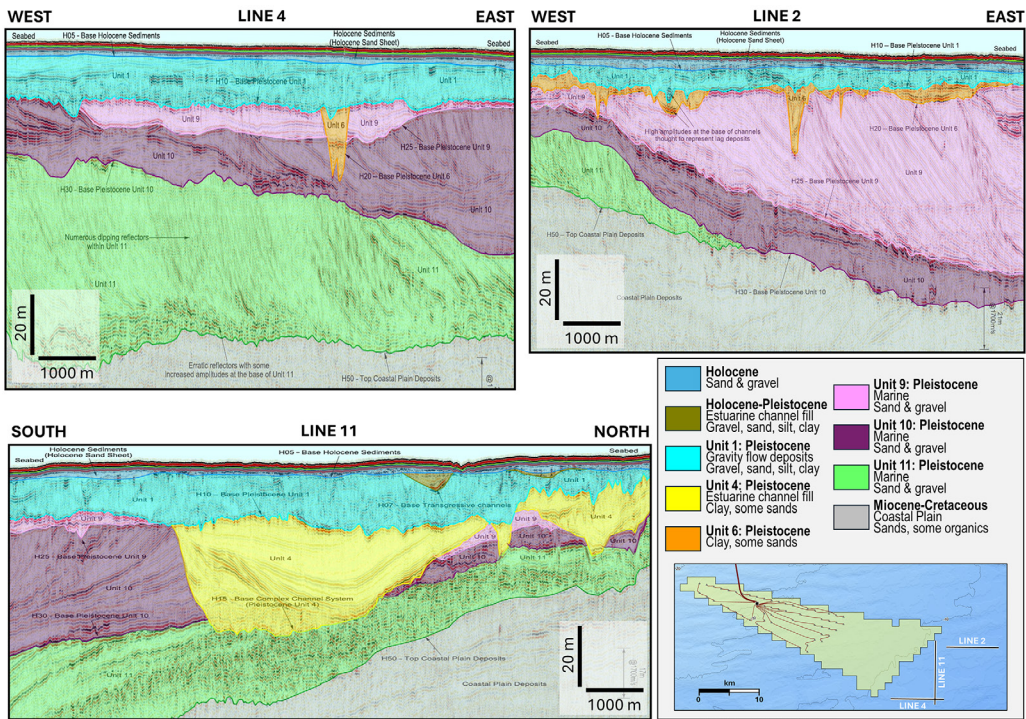


Figure 15: Seismic cross sections located immediately east of the Empire Wind lease (modified from [31], vertical exaggeration  $\sim 50$ ), illustrating geologic complexities across the area. Interpretations are consistent with an initial ground unit framework that was developed across the Empire Wind site, which became increasingly more detailed with time to account for the spatial variability in measured geotechnical properties and seismic reflection characteristics.

#### 4.1.2 Geologic Summary

The Quaternary geology across the New York Bight is diverse. This reflects depositional and erosional processes related to cycles of glaciation and sea level fluctuation through the Pleistocene (2.58 Myr to 11.7 kyr ago) and Holocene (11.7 kyr ago to present day) epochs.

At the maximum of the Wisconsinan glaciation around 20 kyr ago, the Laurentide Ice Sheet extended as far south as Long Island, marked by the Harbor Hill and Ronkonkoma moraines [27], [28]. The Empire Wind site is located 50 km south of the maximum ice extent, in what would have been a periglacial environment (i.e., where the ground is perennially or seasonally frozen) through the Wisconsinan cycle. We, therefore, expect the shallow geology to show a high degree of spatial variability [29], although absent of the complexities that occur at the base and edges

of ice sheets (e.g., tunnel valleys, eskers, drumlins, ground moraine, terminal moraine).

The export cable route remains to the east of the present-day Hudson channel axis (Figure 14) where surficial sediment is dominantly sand, but some regions of till and boulder fields exist. Across the lease area, seafloor gradients are generally less than 1 degree. A 1 to 2 m cover of Holocene (i.e., post-LGM) sand with some gravels has been reworked into broad ridge-and-swale bedforms (<1 m height, up to 2 degrees slope), indicating a degree of sediment mobility. These sediments are underlain by the Pleistocene estuarine, marine and gravity flow deposits comprising gravels, sands, silts, and clays in varying proportions. Rapid thickness changes, channel incisions, and complex cross-cutting geometries occur, and these continue into the region to the immediate east of the lease area (Figure 15).

Table 2: Offshore site investigations performed at Empire Wind. Early Export Cable Routes (ECR) surveys included four routes to potential landfall sites in New York and New Jersey. Excludes metocean, benthic, wildlife, and archaeological surveys. Compiled from several public sources; may not be entirely accurate or complete. TCPT=Thermal Core Penetration Test

Year	Type	Location	Data
2018	Geophysics	Lease	MBES, SSS, MAG, SBP, 2D UHRS multi-channel
	Geophysics	ECR	MBES, SSS, MAG, SBP
	Geotech	Lease	VC, CPT, seafloor samples
	Geotech	ECR	VC, CPT, seafloor samples
2019	Geotech	Lease	BH, CPT, SCPT
	Geotech	ECR	VC, CPT, TCPT
	Geotech	ECR	Seafloor samples
2020	Geophysics	ECR	MBES, SSS, MAG, SBP, 2D UHRS single channel
	Geotech	Lease	VC, CPT, TCPT
	Geotech	Lease	BH, CPT
	Geotech	ECR	BH, VC, CPT
2021	Geotech	Lease	BH, CPT
2023	Geophysics	Lease & ECR	SSS, MAG (UXO clearance)
	Geotech	ECR	VC

This is underlain by partially lithified Miocene-Cretaceous coastal plain deposits, comprising coarse to medium sand with occasional gravel and organic matter [30].

#### 4.1.3 Site Characterization

It is likely that some studies on the ground conditions were performed before the 2016 licensing round and, although details are not available, information may have been similar to that in regional and desktop studies that are now in the public domain (e.g., [30], [32], [33], [34], [35]). These describe the regional geology and highlight the geohazards (e.g., mobile bedforms) and engineering constraints (e.g., boulders, soft soils, communication cables) that future developments would likely encounter.

From 2018 to 2023, several proprietary geophysical and geotechnical surveys were performed across the lease area and along Export Cable Routes (ECRs) (Table 2). High-resolution geophysical data were acquired early

on – including SBP and UHR seismic – which enabled the generation of a ground unit framework to understand the variability measured at geotechnical locations. Although no 3D seismic data were acquired, the 2D lines were closely spaced at ~30 m (with perpendicular tie-lines every 500 m). Geotechnical data were acquired in several phases, beginning with reconnaissance acquisition in 2018 and becoming more detailed and targeted as project plans matured. This ultimately included the acquisition of CPT, BH, and VC data at several hundred locations.

Early results identified the presence of glauconite in Pleistocene and Cretaceous units, an iron potassium mica that can form in shallow marine environments. When stressed, glauconite grains can crush and degrade into clay-like material and change the soil's strength, compressibility, and drainage characteristics. This can lead to increased pile-driving resistance and premature refusal [36],



Figure 16: Monopile installation using a semi-submersible crane vessel, driving the piles to sub-seafloor depths of 50 m (left). Installed 15 MW turbines with a rotor diameter of 260 m, with tips reaching 290 m above sea level (middle). Cable laying along the 75 km route from south Brooklyn to the offshore substation (right).

[37]. In 2019 and 2020, detailed geotechnical data were acquired to understand glauconite distributions and the potential impacts on Empire Wind foundation location, design, and installation. In 2021, recognizing the need for a greater and more regional level of understanding, the Piling in Glauconitic Sand Joint Industry Project was established [38].

Several ground model iterations were performed across the lease area and export cable routes, becoming more detailed as development plans matured and the subsurface complexities became apparent. More ground units were defined and mapped to understand the varying glauconite levels seen in the geotechnical and geological data, and to capture the stratigraphic complexities associated with periglacial environments and fluctuating sea level. A QIGM that was developed toward the end of the Design phase included 46 ground units [39], and the results factored into the project’s decision to install monopiles using a semi-submersible crane vessel (Figure 16).

## 4.2 IJV Gamma Wind Farm Zone, Netherlands

### 4.2.1 Project Summary

The Dutch offshore wind energy roadmap aims

to grow offshore wind capacity to 21 GW by 2032 and 50 GW by 2040. The IJV area was identified in 2019 as one of the development areas, and the 278 km<sup>2</sup> “Gamma” portion is located about 60 km offshore where water depths range between 23 and 35 m (Figure 17). A licensing round is being planned that includes the development of two wind farms (Gamma-A, Gamma-B), each with a generation capacity of 1 GW.

### 4.2.2 Geologic Summary

The upper 100 m of ground is comprised of Pleistocene and Holocene sediments with a complex layering that records three cycles of glaciation [40]. The deepest layers of interest were deposited over 500 kyr ago in systems flowing in from the east. These deposits include cycles of deltaics coarsening up to fluvial sands, with regional unconformities and deep channel cuts.

Glaciation cycles intensified from the mid-Pleistocene, and ice advanced across the IJV Gamma site during the Elsterian glaciation (500-421 kyr ago), carving deep tunnel valleys that were filled by a succession of till and marine mud. As the ice retreated, a network of braided rivers cut fluvial channels that were filled by a mix of clastic lithologies

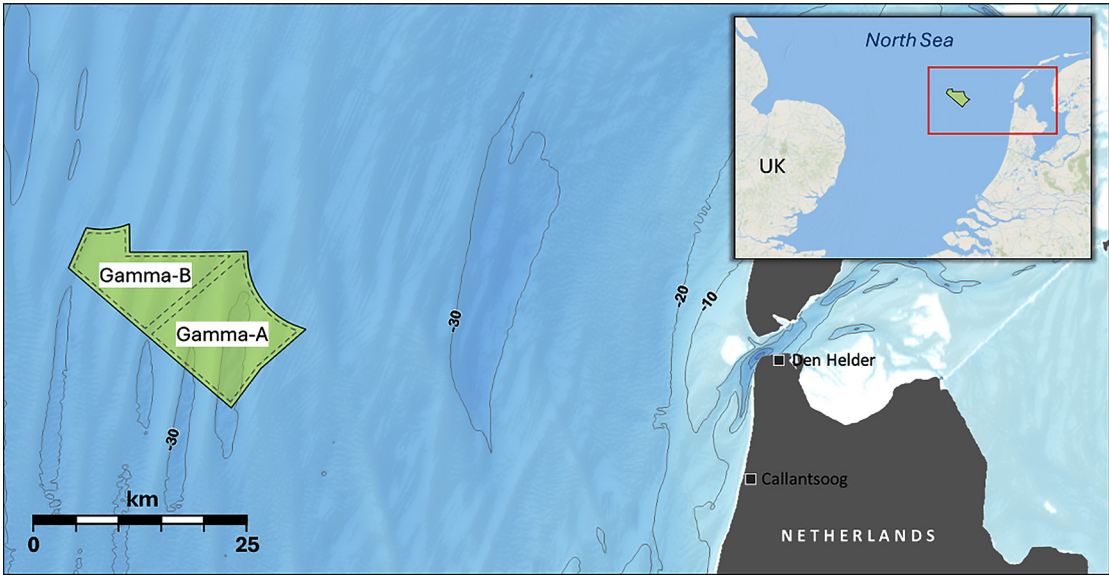


Figure 17: Location of the IJV Gamma wind farm zone, where two projects are planned (Gamma-A, Gamma-B). The ~60 km long export cable route to shore is not yet defined.

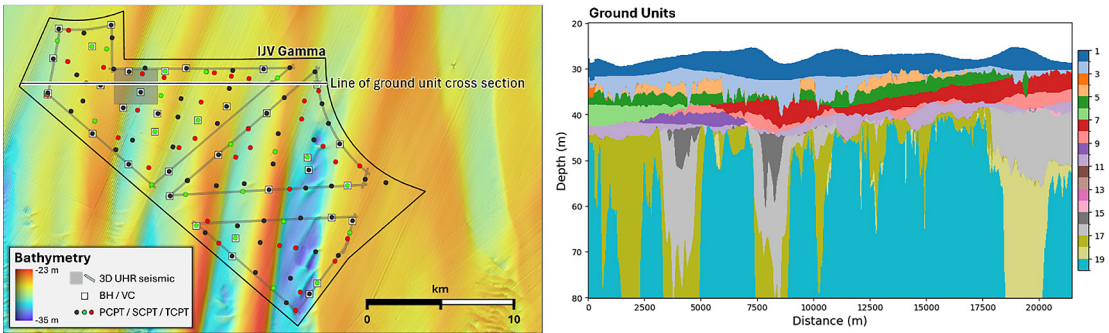


Figure 18: Bathymetry map showing location of geophysical and geotechnical site investigation data; 2D seismic not shown but was acquired across the entire IJV Gamma site (left). West-east geologic cross section showing 19 ground units (right).

until rising sea level saw the deposition of open marine fine-grained sand, silt, and clay.

During the Saalian glaciation (395-130 kyr ago), sea level fell again, and the environment transitioned from marine, to coastal, and ultimately to terrestrial periglacial conditions. Sediments include cycles of terrestrial, shallow marine, and meltwater plume deposits. Ice advanced to within ~50 km of the site from where it began to retreat, and the rising sea levels again resulted in transgressive erosion and deposition in a succession of fluvial, coastal, and marine environments.

The maximum extent of glacial ice during the Weichselian phase (115-12 kyr ago; equivalent to the Wisconsinan in North America) lies ~100 km from IJV Gamma, and the associated low sea level exposed the site again and periglacial conditions returned. With glacial retreat during the early Holocene, sea level rise created a marine transgressive surface with a complex system of channels filled with lagoonal, littoral, and fluvial sediments. On top of these we see high energy open marine deposits that form the waves and ripples of today's seafloor (see Figure 18).

Table 3: Offshore site investigations performed at IJV Gamma, in chronological order. Excludes metocean, benthic, wildlife, and archaeological surveys.

Year	Type	Location	Data
2021	Geotech	Lease	BH, CPT (reconnaissance, 12 locations)
2022	Geophysics	Lease	MBES, SSS, MAG, SBP, 2D UHRS multi-channel
	Geophysics	Lease	3D UHRS (7 km <sup>2</sup> area)
2023	Geotech	Lease	VC, CPT, TCPT, seafloor samples
	Geophysics	Lease	MBES, 3D UHRS corridors (3 loops, 110 m wide, 125 km)
	Geotech	Lease	Seafloor / shallow samples
2023-4	Geotech	Lease	CPT, SCPT, TCPT (shallow phase)
	Geotech	Lease	BH, CPT, SCPT, wireline (deep phase)

#### 4.2.3 Site Characterization

A DTS was completed in 2019 that formed the basis for initial site investigation plans. After a reconnaissance geotechnical survey in 2021 (12 locations, to depths of 80 m), 2D seismic data – both SBP for shallow imaging and multi-channel UHR to image down to 100 m – were acquired across the entire lease, with 70 m inline spacing (oriented NNE-SSW) and 420 m crossline spacing for a total of 5,700 line km. The detailed geotechnical campaigns were planned so that CPTs, BHs, and VCs were located precisely on geophysical survey lines. In total, core samples were retrieved from 36 locations and CPTs were acquired at 115 locations (includes piezo, seismic, and thermal CPTs) with penetrations down to 80 m (Table 3; Figure 18).

Understanding and interpreting the features associated with the glaciation cycles and sea level fluctuations was critical to the development of the ground unit framework. This comprised of 19 units mapped on the UHR seismic data (in TWT) which, when converted to depth, lined up with geotechnical changes seen on the CPT data. This effectively segmented a highly variable distribution of lithologies, across which we

see sharp contrasts resulting from different depositional environments, regional erosion, and steep-sided channels.

With the framework in place, visualizing data in a QIGM generated an understanding of the ground conditions critical to early design decisions. For inter-array cables, measured variability in sediment cohesiveness and thermal conductivity was related to the presence of specific ground units, notably channel systems and periglacial landforms mapped within the Holocene. For OWT foundations, the ground model enabled the identification of areas with higher risk of sediment remobilization (e.g., related to differential compaction above tunnel valley margins) and greater likelihoods of encountering constraints caused by the presence of boulders, organic matter, and free gas.

RVO required a QGM that could generate geotechnical design profiles with uncertainty envelopes. A 3D grid was generated from the ground unit framework with over 1.3 billion cells, each measuring 25 m by 25 m in map view and 0.1 m in thickness. Each cell was initially attributed with its depth below the seafloor and with one of the 19 ground units.

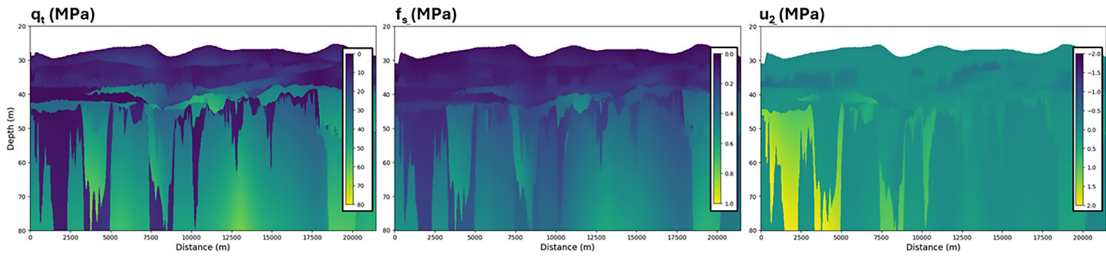


Figure 19: Example results from geostatistical prediction of Core Penetration Test (CPT) properties  $q_c$ ,  $f_s$ , and  $u_2$ . Results capture the spatial variability in depth trends within each unit. The line of section is shown in Figure 18.

The simplest predictions involved defining depth trends, with both global linear (i.e., a single gradient and intercept per unit) and geostatistical (i.e., spatially varying trends per unit) approaches. This underscores the importance of an accurate ground unit framework as these will bracket intervals of low variability and thus highest predictability. Figure 19 shows geostatistical predictions for three CPT properties (corrected cone tip resistance,  $q_t$ ; sleeve friction,  $f_s$ ; pore pressure response,  $u_2$ ). Benefits of these baseline methods (see Figure 13) are that they are computationally fast, produce predictions that are closely aligned with engineering best practices, account for lateral variability (in the case of the geostatistical approach), and can be readily applied from early-phase through to final site characterization.

More advanced machine learning methods were also tested and applied, including using Artificial Neural Networks (ANNs) with seismic inversion parameters to predict both CPT and engineering properties along all 2D seismic lines. First, pre-stack elastic inversion generated 2D sections of acoustic impedance ( $Z_p$ ), shear impedance ( $Z_s$ ), bulk density ( $\rho$ ), and seismic quality factor ( $Q_p$ ). From these, the small-strain shear modulus ( $G_{max}$ ) was estimated (i.e.,  $Z_s^2/\rho$ ), and ANNs were trained to predict CPT and other

geotechnical parameters (e.g., undrained shear strength,  $s_u$ ; peak friction angle,  $\phi$ ). This machine learning workflow was probabilistic, using an ensemble of ANNs to capture and propagate uncertainties from the seismic inversion and training data into the final predictions.

A final step involved interpolating the predictions from the 2D seismic lines to populate the entire 3D model. This interpolation was guided by a “stratigraphic index,” a fine-scale subdivision of each ground unit that assigned one of over 3,500 relative geologic ages to each model cell based on the unit’s depositional model. This approach allowed property prediction to be guided by grouping synchronous deposits, across which variability is expected to be most predictable. Figure 20 shows results along the same west-east cross section used in Figure 18 and Figure 19.

In the future, companies will be invited to bid for the Gamma-A and Gamma-B licenses. The QGM results have generated a good understanding of the spatial variability in ground conditions that will allow developers to quickly build robust project plans and may eliminate the need for further site investigations. The associated cycle time reduction should lead to higher value projects.

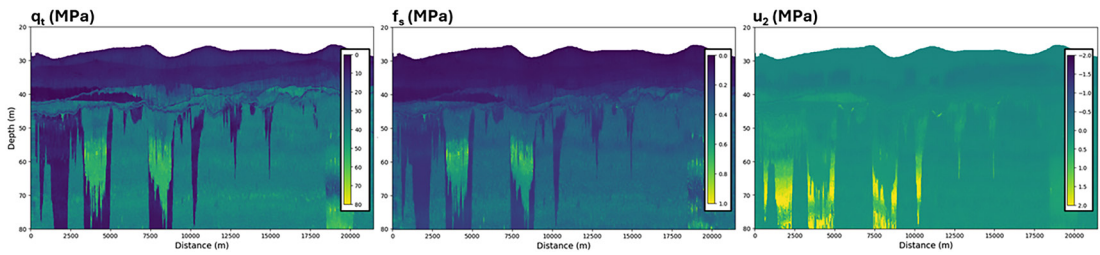


Figure 20: Example results from Artificial Neural Network (ANN) prediction using seismic inversion properties trained on Core Penetration Test (CPT) data. Results capture the variability in seismic impedance (and other seismic and inversion properties) within each unit. The line of section is shown in Figure 18.

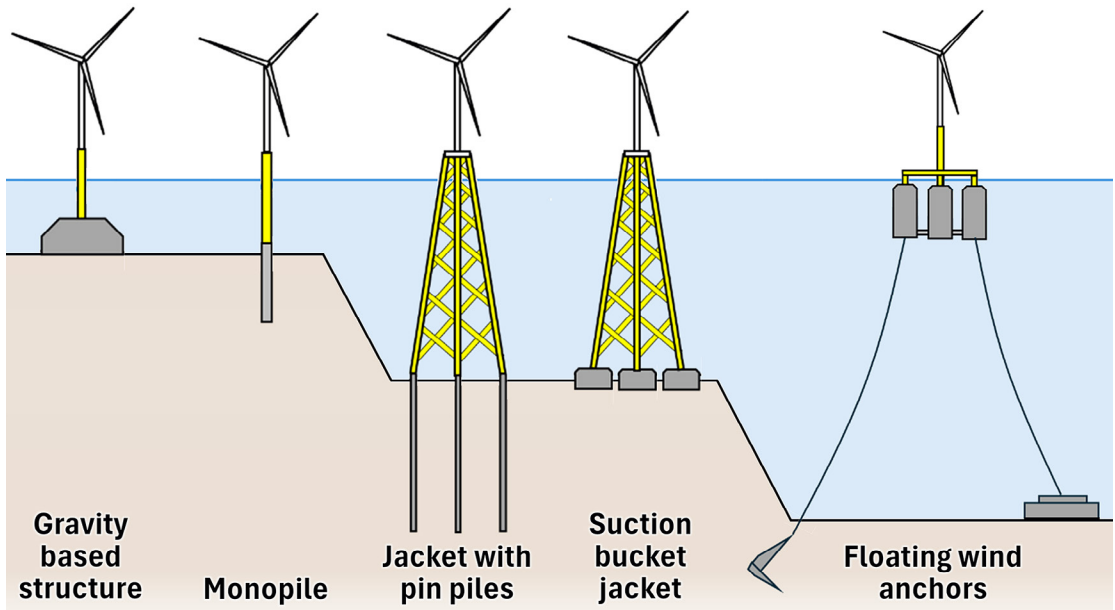


Figure 21: Offshore Wind Turbine (OWT) foundation concepts that are likely in play offshore Nova Scotia.

## 5. NEXT STEPS FOR NOVA SCOTIA

A recent DTS [1] integrated public-domain research and data to describe the shallow geology across the shelfal areas of Nova Scotia. While confidentiality prevents us from including detail, the study concludes that suitable ground conditions likely exist and indicates where a range of fixed and floating concepts (Figure 21) may be best suited (Figure 22).

The DTS may help potential developers with Screening decisions ahead of planned licensing

rounds, the first of which is expected to conclude in 2026 with the issuance of three or four Submerged Land Licences. Additional data will also become available, including survey results from GSC expeditions and legacy oil and gas data that may be repurposed to provide information on near-surface ground conditions (e.g., [41]). The value of these data will likely be highest when integrated with DTS results.

A significant amount of new data will be needed across acquired leases and along their potential export cable corridors. Project value will likely be generated from high-resolution

Geohazards	Potential impacts
Mobile bedforms	Sediment build-up around foundations; cable damage e.g., burial, uncovering
Sediment scour	Foundation stability; cable damage e.g., uncovering, freespan
Fluid expulsion	Methane release; seafloor instability; foundation integrity; cable damage
Slope instability	Slumps & gravity flows; foundation & cable damage
Earthquakes	Ground shaking; liquefaction; fluid expulsion; slope instability; tsunamis
Tsunamis	High wave loads; sediment scour; foundation weakening; cable damage
Salt movement	Seafloor movement; foundation integrity
Coal mine collapse	Seafloor collapse; foundation integrity & cable damage
Engineering constraints	Potential impacts
Heterogeneous properties	High geotechnical variability; sub-optimal location & design decisions
Abnormal properties	Extreme geotechnical conditions; sub-optimal location & design decisions
Boulders	Surface & buried obstacles to foundations and cables
Shallow bedrock	Foundation refusal / damage, poor cable trenching / protection
Shallow gas	Reduced foundation capacity; gas release
Rugged / steep seafloor	Foundation & cable laying challenges; cable freespan
Existing infrastructure	Foundation & cable laying obstacles / challenges
Shipwrecks, debris, UXO	Foundation & cable laying obstacles / challenges

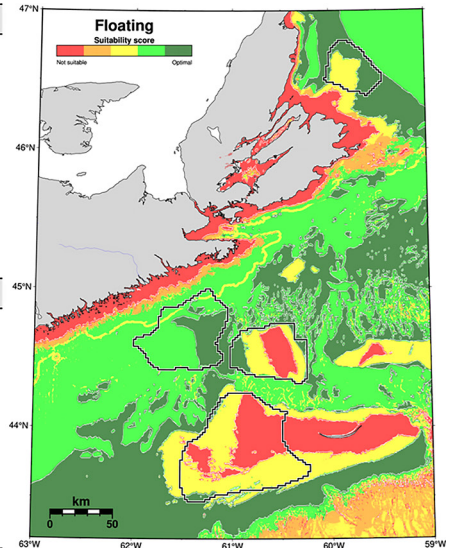


Figure 22: Geohazards and engineering constraints identified and mapped across the Wind Energy Areas (WEAs; left). Map shows the suitability of a single Offshore Wind Turbine (OWT) foundation concept to water depths and ground conditions (right). UXO=Unexploded Ordnance

geophysics and, in areas of high geologic complexity, we expect the acquisition of 3D seismic to be desirable in the first phase of site characterization.

Early alignment between geoscientists and engineers should be established through the development of a ground unit framework, generating a common understanding of project critical uncertainties and the data/analyses required to reduce them. As more geophysical and geotechnical data are acquired, the ground model should be updated to serve as the basis for site investigation, project layout, and engineering design decisions.

In some areas, we anticipate that QGMs will be needed to predict geotechnical design parameters (and their uncertainty envelopes) at locations where additional geotechnical acquisition may be cost prohibitive. Recent advancements in seismic acquisition, data processing, seismic inversion, and machine learning may generate reliable predictions,

enabling detailed design and installation away from points of geotechnical measurement. These surveys will need to be planned, acquired, and processed with care to maximize data quality and retain amplitude variation with offset compliance.

Success will require a high level of coordination and aligned effort across regulators, local communities, manufacturers, suppliers, and developers, as well as experts in geoscience and engineering. Nova Scotia may also benefit from the experiences and lessons learned at offshore wind developments located in formerly glaciated regions, such as those discussed in this paper.

## 6. CONCLUSION

Around 20 kyr ago, the areas being considered for offshore wind development in Nova Scotia lay beneath the great Laurentide Ice Sheet. We expect the upper 100 m of the seabed to present a complex mosaic of

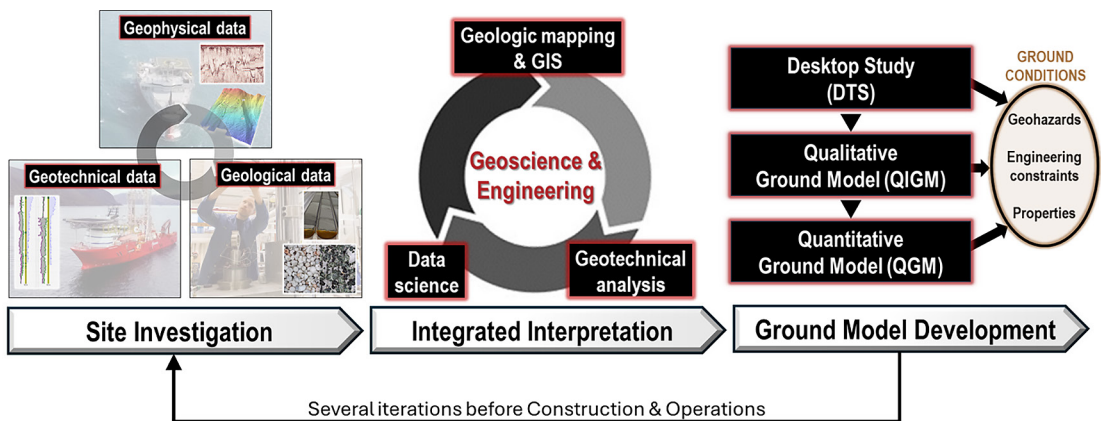


Figure 23: General site characterization workflow. Several cycles of integrated data acquisition and interpretation are typically performed through project Screening, Selection, and Design (see Figure 6). As a project matures and the volume of data grows, the level of detail in its ground model increases from a Desktop Study (DTS) to a Qualitative Ground Model (QIGM), and areas of high geologic complexity may ultimately require a Quantitative Ground Model (QGM).

geohazards, engineering constraints, inter-fingering lithologies, and heterogeneous geotechnical properties. This is supported by a recent DTS [1] and by site characterizations for offshore wind developments on geologically analogous terrains.

The ultimate success of an offshore wind development is enhanced by accurate site characterization (Figure 23), which enable stakeholders to:

- **Select the Best Project Sites:** In the absence of detailed data, an integrated analysis of publicly available information can be critical to Screening decisions. A DTS that accurately represents the nature and expected complexity of ground conditions can lead to the identification of feasible concepts and favourable areas and, therefore, to good licensing decisions.
- **Maximize the Value of Data:** Site investigation is generally phased over the first few years of development. Significant project value can be generated

when the level of detail in the initial phase matches the complexity of ground conditions. This may especially apply to decisions concerning the acquisition of high-resolution 3D seismic data. Geophysical and geotechnical surveys need to be carefully designed and considered in partnership with the wider project objectives, targeting areas of critical subsurface uncertainty that are recognized in the evolving ground model.

- **Optimize Infrastructure Location and Design:** As more geophysical, geotechnical, and geological data are acquired, their integrated interpretation generates a 3D representation of ground conditions (i.e., geohazards, engineering constraints, and soil/rock properties) as a ground model. A critical step is the establishment of a robust ground unit framework – this requires geoscientists and geotechnical engineers to develop a common understanding of the nature and consequences of ground heterogeneity, and to define and map the minimum number of units that adequately capture

it. In early stages of development, QIGMs may be used to make high-level project decisions and to identify areas of critical uncertainty for more focused site investigation. As the development matures, the ground model can become increasingly more detailed with more ground units. In areas where variability is not adequately captured by geotechnical measurements, it may be necessary to predict properties with a QGM for final infrastructure location and design decisions.

Nova Scotia has a bold vision for offshore wind, and successful projects from its early licensing rounds are needed for the journey that lies ahead. Accurate site characterizations will be critical to reducing the time needed to ensure the right project facilities with the right designs are installed at the right locations. The result will be shorter payout times and increased profitability, which will encourage long-term investment and the continued development of Canada's vast offshore wind resource.

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#### Authors' Declaration

- Funding: The authors did not receive financial support from any organization for the submitted work.
- Ethical approval: This paper does not contain any studies with human participants or animals.
- Competing interests: The authors declare that they have no competing interests.
- Availability of data and materials: Datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.
- Artificial intelligence was not used in this work.

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