Metocean and Geotechnical Design

Offshore wind development

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Who should read this paper?

This paper is intended for offshore wind developers and technical teams, including metocean and ice specialists, geotechnical, structural, and naval architectural engineers, and power performance modellers. The paper is also relevant to organizations involved in the planning, design, and approval of offshore wind projects in cold and ice-affected regions, including government stakeholders, energy boards and regulators, and certification authorities.

Why is it important?

This paper presents a regional assessment of the environmental inputs and the structural response of offshore wind turbine structures for Atlantic Canada, considering both fixed (monopile) and floating (semi-submersible) support structures. To the authors' best knowledge, this is the first published study to evaluate multiple turbine operating modes (production, idling, and parked) across a range of environmental conditions, including operational winds, extreme hurricanes, winter storms, sea ice, and varying seabed properties for Atlantic Canada. The study integrates coupled aero-hydro-servo-elastic simulations to compare nacelle accelerations, blade tip deflections, structural forces and moments, seabed shear and moments, icing accumulation, and preliminary mooring and anchoring considerations.

It provides an initial design basis and benchmarking reference for offshore wind development projects in Atlantic Canada; it is applicable to both fixed and floating platforms. The paper also highlights topics such as critical data availability issues and knowledge gaps, helping guide future measurement programs, modelling efforts, and risk-informed design studies. Further, it highlights some of the implications of intermediate water depths on the selection of fixed versus floating support structures.

About the authors

Dr. Freeman Ralph joined C-CORE in 1999 and is presently vice president of oceans and energy having over 25 years of offshore oil and gas and alternative energy expertise. He holds three degrees from Memorial University including a bachelor's degree in naval architecture and ocean engineering, a master's degree in ship ice interaction modelling, and a doctorate degree focused on ice mechanics, ship structures, and probabilistic design. His experience includes offshore structure and ship design; environment characterization and design basis, risk analysis and probabilistic methods including extreme event and risk mitigation modelling, icing occurrence, mitigation, and operations interruption; and design and protection of subsea infrastructure including geotechnical foundation and mooring considerations.

Paul Stuckey joined C-CORE in 2003 and is currently deputy director of ice and ocean engineering. He is a professional engineer with over 25 years of experience in ice and ocean engineering, leading studies in environmental characterization, design load estimation, environmental and ice-related downtime modelling, structural analysis, and the dynamic response of fixed and floating offshore wind turbines under combined wind, wave, and ice conditions. He has made significant contributions to major developments offshore eastern Canada, including Hebron, West White Rose, and Bay du Nord, providing the clients with design basis support from concept selection stage through to detailed engineering.

Dr. Mark Fuglem is a principal consultant at C-CORE, with over 40 years of experience, including application of probabilistic methods to determine design loads on structures, extreme event analysis, optimization of offshore oil transportation systems, risk and reliability assessments and input on design codes, and estimation of environmental downtime for offshore operations, considering forecast uncertainty, weather windows and downstaffing by helicopter, walk-to-work, and frog. Recent work includes characterization and evaluation of wind and ice load effects on fixed and floating offshore wind turbine structures, and development of a 12-DOF impact load model for floating offshore wind turbines.

Gerry Piercey

Arijit Biswas Arghya holds a master of engineering and specializes in numerical modelling and geohazard analysis. He has experience in slope stability and seepage analysis, debris-flow runout modelling, pipe-soil interaction, and offshore anchoring and foundation design under complex loading conditions. At C-CORE, he has supported major offshore and onshore projects through geotechnical characterization, geohazard analysis, finite element modelling of various anchors and buried pipelines, and development of GIS-based landslide risk maps for industry partners. He also contributes to C-CORE's experimental systems and data-driven modelling efforts, applying his programming skills to enhance the integration of field, laboratory, and numerical data for advanced geotechnical problem-solving. His master's research at Memorial University focused on debris-flow runout simulation using empirical and continuum approaches to improve geohazard prediction.

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Gerry Piercey's background is mechanical engineering, systems engineering, centrifuge modelling, and project management engineer with bachelor's and master's degrees in mechanical engineering. Working as the team lead, he manages the C-CORE laboratory and large-scale geotechnical centrifuge. His experience also includes the design, manufacturing, and commissioning of unique field equipment and unique project focused experimental equipment and the execution of the experiments for a variety of industries and projects. He has executed a wide range of centrifuge experimental projects including suction caisson performance, suction embedded and flexibility embedded plate anchors in different loading conditions, frost heave of buried pipelines, surface loading of buried pipelines, and ice soil pipe interaction studies.

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Dr. Ahmed Derradji-Aouat works with the National Research Council of Canada (NRC) in St. John's, NL, Canada. He performs numerical simulations using advanced multi-physics software and conducts experimental work using the NRC ice tank and other large open water wave tanks. In recent years, he focused his technical work on offshore wind energy projects and uses his numerical models to predict the environmental loads (including ice loads for ice covered waters) on offshore wind turbines. The experimental tank testing work provides data to verify and validate the numerical models and simulations.

OFFSHORE WIND DEVELOPMENT IN ATLANTIC CANADA: REGIONAL METOCEAN AND GEOTECHNICAL DESIGN CONSIDERATION AND OPPORTUNITIES

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DOI: https://doi.org/10.48336/NHP0-M641

ABSTRACT

Offshore Atlantic Canada has enormous potential for developing wind farms given the strong winds in the region and experience developing offshore oil and gas facilities. Depending on the specific location, there can be hurricanes, strong winter storms, sea ice, icebergs, and icing conditions. Other considerations include the varying water depths, seabed soil conditions, distances to shore, and port and electricity infrastructure. The electricity demand also varies between the four provinces.

Wind turbine structures are designed to be relatively light. As a result, environmental loads can result in significant non-linear effects with coupling between the turbine and supporting structure responses, and susceptibility to fatigue. The choice of structure type will be critical. A significant part of the region is at water depths that are intermediary between those ideal for fixed and floating structures.

The present work provides an overview of the conditions across the region and specific challenges and information gaps. It builds on previous studies of the applicable standards, such as IEC 61400-3-1 and -2, the variation of wind conditions over the region, the relative severities of hurricanes versus winter storms, and the potential for sea ice and iceberg impact loads on floating and monopile support structures. Example OpenFAST analyses are presented for monopile and semi-submersible systems to demonstrate the potential influence of soil conditions on the structural response of the monopile and mooring and anchoring considerations for the semi-submersible. The risk of icing and potential downtime is assessed.

Keywords: Offshore wind, Atlantic Canada, metocean, hurricanes, winter storms, icing, geotechnical, moorings, downtime

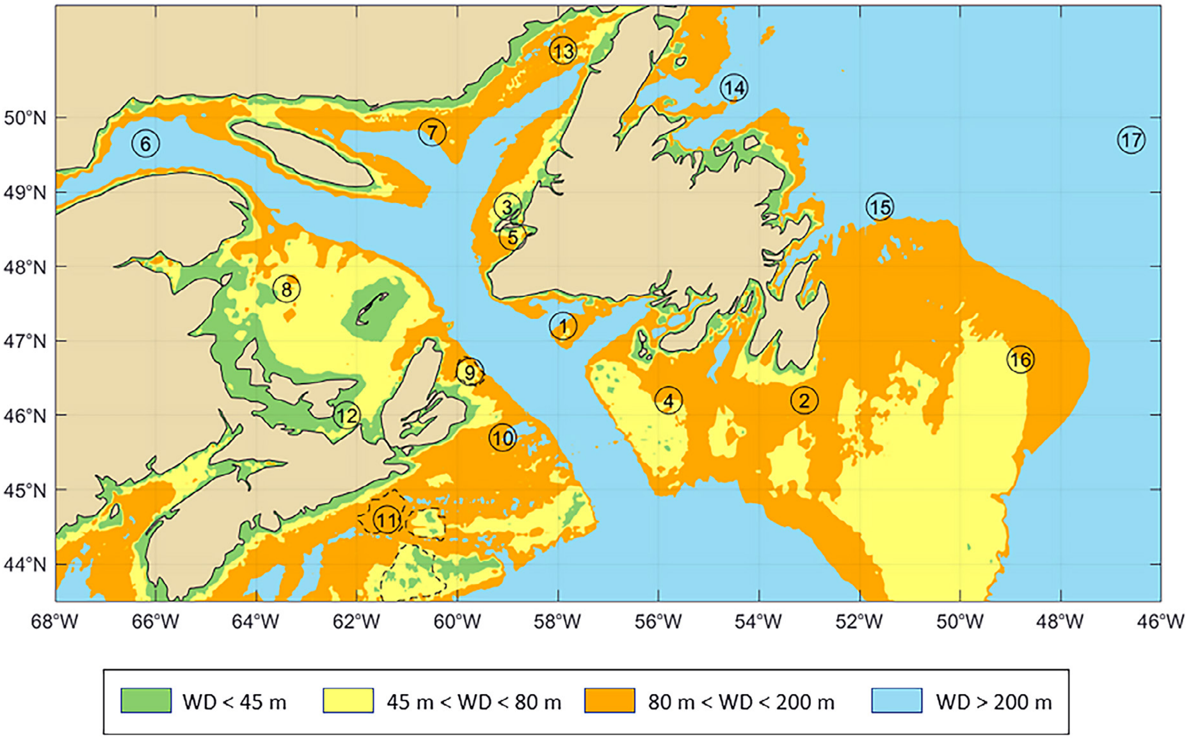


Figure 1: Region of interest showing key water depth ranges and example sites; based on [1].

1. INTRODUCTION

Atlantic Canada has substantial energy potential having strong offshore winds and large areas with suitable water depths for bottom-founded or floating wind turbines. The region of consideration is shown in Figure 1, with 17 locations identified to characterize the ice and metocean conditions [1].

Environmental parameters are provided for the sites to highlight differences in conditions that could influence the installation of wind farms. Important metocean parameters include average and extreme winds, currents, waves, sea ice, icebergs, visibility, and parameters related to potential icing. Water depth and soil conditions strongly influence the choice of viable platforms; the green, yellow and orange areas correspond to water depths less than 45 m, 80 m, and 200 m, respectively.

Designing Offshore Wind Turbines (OWTs) for Atlantic Canada requires comprehensive evaluation of extreme aerodynamic, hydrodynamic, and ice-induced loads, particularly under parked mode conditions when turbines are idling or shut down during severe weather. While wind and wave effects are well studied, the presence of sea ice introduces additional complexities due to limited environmental data and modelling challenges related to ice-structure interaction.

This paper presents numerical simulations of environmental loads on a 15 MW OWT operating in production and parked modes subjected to wind, wave, current, and ice loads. Building on a prior regional assessment of 17 potential offshore wind sites in Atlantic Canada [1], this study focuses on offshore turbines situated in two water depths: 45 m and 150 m. The 45 m water is representative of shallow water conditions in regions such as offshore western Newfoundland (e.g., Site 3 in Figure 1). This location is within the range suitable for monopile foundations. The second location has a water depth of 150 m, representative of conditions for a floating foundation such as a semi-submersible.

The simulations utilize OpenFAST, a widely used, open-source aero-hydro-servo-elastic simulation tool, to capture coupled turbine and environmental interactions. Several IEC 61400 Design Load Cases (DLCs) specific to the production and parked design situations were selected to examine the responses of the turbine and the platform to typical production loads and extreme loads such as that from hurricanes. This approach enables a comprehensive assessment of how environmental factors differ in impact between ice and non-ice seasons and the combined loading effects on critical turbine components including the tower, substructure, and nacelle.

The results emphasize important design considerations unique to Atlantic Canada and identify significant gaps in environmental data especially related to sea ice thickness and dynamics. These findings support the development of more robust design and operational strategies to harness offshore wind energy safely and efficiently in cold-climate regions.

2. RELEVANT STANDARDS

The development and design of OWTs are governed by a combination of national regulations, international standards, certification practices, and, in some cases, classification requirements. The International Electrotechnical Commission (IEC) and DNV publish standards that define the principal technical requirements for offshore wind farms, while referencing International Organization for Standardization (ISO) standards for more general offshore design and operational considerations. In parallel, certification bodies and classification societies such as DNV, ABS, Bureau Veritas, and Lloyd’s Register publish guidelines for fixed and floating offshore wind structures. These generally align with the design situations and load cases defined in the IEC standards, but may introduce additional requirements related to certification, classing, inspection, and life cycle assurance.

IEC 61400-3-1 (fixed OWTs) and IEC 61400-3-2 (floating OWTs) address design for the offshore environment, including wind, waves, and ice for structures such as monopiles, jackets, spars, semi-submersibles, and Tension-Leg Platforms (TLP). A set of defined design situations (including power production, fault conditions, start-up, shutdown, parked, and transport conditions) is combined with prescribed DLCs involving wind, wave, current, and water level conditions. These load cases are evaluated for ultimate and fatigue limit states using partial safety factors that distinguish between normal and abnormal conditions.

OWTs are highly non-linear systems due to the interaction between aerodynamic loading, turbine control systems, structural dynamics, and hydrodynamics. As a result, compliance with DLCs requires coupled time-domain simulations using stochastic environmental inputs. Key response parameters include structural forces and moments, nacelle accelerations, blade deflections, and, for floating systems, platform motions and mooring line tensions. Fatigue damage accumulation is a critical design consideration, particularly for moorings, weld details, and dynamic electrical cables.

In Canada, the Canadian Standards Association (CSA) is accredited by the Standards Council of Canada to develop and maintain national standards. CAN/CSA C61400-3 was adopted from IEC 61400-3:2009 with Canadian deviations. Following the division of IEC 61400-3 into separate fixed and floating standards, CSA is in the process of adopting IEC 61400-3-1 with Canadian deviations, while a decision on adoption of IEC 61400-3-2 has not yet been made. As a result, floating offshore wind projects in Canada may rely directly on IEC or DNV standards, subject to regulatory acceptance.

Several proposed Canadian deviations to IEC 61400-3-1 relate to ice loading, reflecting the significant regional variability in ice conditions offshore eastern Canada. In many areas, ice advects into the region rather than forming locally, and the characteristics of ice features and interaction mechanisms can differ substantially from those assumed in generic offshore wind guidance. It has, therefore, been suggested that ice loads be determined using ISO 19906, which provides a more comprehensive framework for ice-structure interaction across a wider range of metocean and ice conditions. Direct calculation of ice loads, rather than reliance on level-ice thickness alone, may also better capture local effects, including non-horizontal loading components.

DNV offshore wind standards, including DNV-ST-0126 for fixed structures and DNV-ST-0119 for floating structures, define design situations and load cases broadly consistent with IEC, but differ in load calculation methods, safety factors, and treatment of regional conditions. DNV standards also address accidental loads such as vessel collision and dropped objects, and provide detailed guidance on ice crushing, bending, splitting, and ridge loading. Compared to IEC, the ISO 19900-series standards employ higher return periods and explicitly define abnormal limit states for manned hydrocarbon facilities; OWTs, being unmanned and without hydrocarbon storage, generally adopt less stringent criteria.

Beyond regulatory compliance, project developers may elect to pursue either certification alone or full classification. Certification demonstrates compliance with applicable standards at the design and construction stages, whereas classification typically includes ongoing inspection and verification throughout the operational life of the structure. Insurers and lenders often view classification as reducing project risk, particularly for floating wind turbines and novel structural concepts, and this can influence the choice of standards and conformity assessment route. These considerations are particularly relevant in eastern Canada, where offshore wind development must address large variations in

Table 1: Structure types and depth ranges.

Structure	Depth Range (m)	Comments
Fixed		
Gravity based	5 to 50	• Costs increase significantly with water depth and associated increased overturning moments due to waves. • Need a well-prepared and sufficiently solid base.
Steel Monopile	5 to 70	• Most common support structure for offshore wind turbines. • Higher range for extra-large monopiles, but these have increased weight and cost.
Jacket	5 to 100	• Simple, conventional gravity based offshore support structure.
Guyed Monopile/Truss	Up to 150	• Simple, single column. • Light weight, small footprint.
Articulated Wind Column	70 to 250	• Novel, no guyed wires. • Single footprint; no anchors.
Floating		
Spar	Greater than 100 m	• Spars typically have drafts in the range of 80 to 120 m and so require greater water depth.
Semi-submersible	50 to 500	• Wide range of structure types consisting of cylinders, columns, and pontoons. • Conventional spread mooring systems.
Tension-Leg Platform	Greater than 40 m	• Needs very strong vertical anchoring.

water depth, soil conditions, ice regimes, and infrastructure constraints, and where experience with offshore wind remains limited.

Offshore substations are generally treated as intermittently manned installations and are, therefore, subject to more stringent safety requirements than turbine support structures. While IEC 61400-3-1 and -3-2 provide a wind-specific framework, substations are typically designed using offshore platform standards such as ISO 19900 series, together with classification society rules. This introduces explicit consideration of accidental and abnormal limit states, higher environmental return periods, and additional load cases such as vessel impact and fire. These requirements become particularly influential for floating substations and for developments in ice-prone waters.

3. STRUCTURES

There are a number of different support structures available for OWTs, ranging from fixed-bottom concepts to different floating solutions. Table 1 provides a summary of the different types of support structures, the associated water depth range, and some general comments. Monopiles work well in water depths up to approximately 45 m, provided soil conditions are sufficiently stiff, while jacket structures extend the feasibility of bottom-founded structures up to 100 m water depth but with increased cost and installation complexity. Beyond 100 m depth, floating concepts, such as semi-submersibles, spars and TLPs, are suitable due to their broad depth. Spar platforms typically require greater water depth due to their large draft. Floating concepts typically require three or four mooring lines. Mooring system layouts can become quite complex for larger

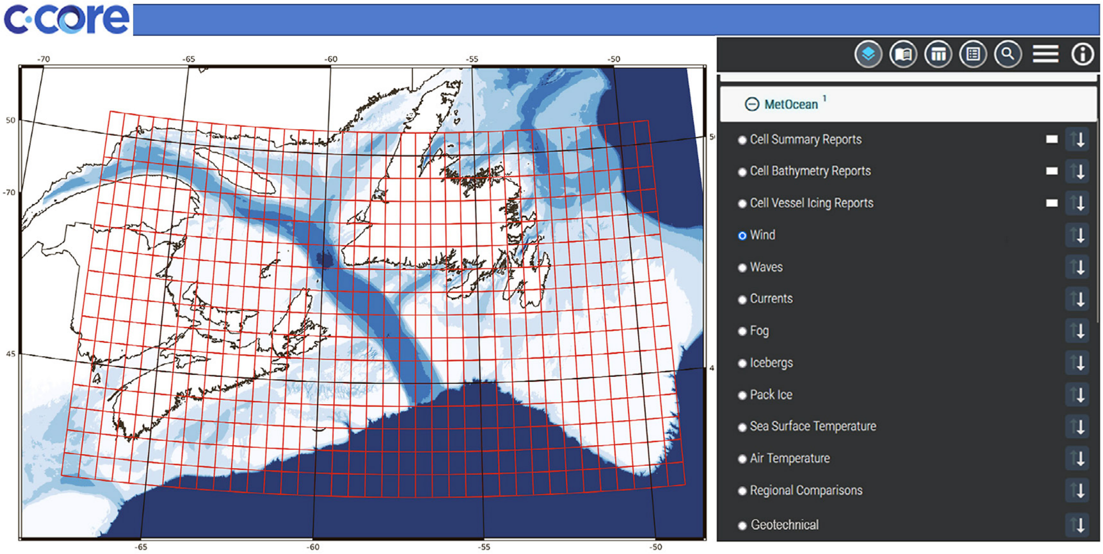


Figure 2: Atlantic Canada Wind Development Database.

wind farms and the idea of shared anchors to reduced costs and environmental footprint has been considered. TLPs require vertical anchoring that may be challenging in glacial soils. There are several new novel concepts that bridge the gap between monopiles and semi-submersibles, including the Entrion Fully Restrained Platform Monopile [2], the OSI Renewables FTLP Wind Platform [3], and the AWC Tech Articulated Wind Column [4]. The overlap in water depth ranges highlights that support structure selection in Atlantic Canada is governed not only by water depth, but also by soil stiffness, environmental loading, and installation constraints. As a result, comparing monopile and semi-submersible concepts at similar turbine ratings provides a meaningful assessment of structural response across the fixed-to-floating transition that is highly relevant for regional offshore wind development.

4. METOCEAN AND ICE CONDITIONS

4.1 Overview

Atlantic Canada offshore region is characterized by varying metocean and ice conditions. To support developments, C-CORE is building an ice, metocean, environmental, and geotechnical design focused database for Atlantic Canada to assist in enabling wind energy development. The regional coverage of the database and the included parameters are shown in Figure 2. The database will provide detailed statistics on historical metocean and ice conditions for a range of variables within defined grid cells over the region of interest. The database is modelled after Insight (https://insight.oilconl.com/ReportViz/Index), which is an ice and metocean database for offshore Newfoundland and Labrador developed for OilCo. The new database will offer onshore and offshore wind developers an initial planning tool to de-risk Atlantic Canada by providing information needed to make design and investment decisions on where to develop wind farms that optimize design and power generation and minimize downtime and maintenance costs. A listing of the datasets and corresponding qualifiers is given in Table 2.

Table 2: Data sources in wind development database for Atlantic Canada.

Data Source	Qualifier
Wind: ERA5	Re-analysis dataset from the European Centre for Medium-Range Weather Forecasts providing hourly, gridded hindcast wind data on land and ocean from 1940s to present.
Waves: MSC50 dataset	Hindcast wind and wave dataset for offshore Canadian waters developed by Oceanweather Inc. for Meteorological Services of Canada, Environment and Climate Change Canada. Contains either hourly or three-hour recordings of wind and wave values for 68 years from 1954 to 2021, measured in m/s at a height of 10 metres above mean sea level.
Current: Hybrid Coordinate Ocean Model (HYCOM)	The HYCOM database covers a temporal range of 22 years from January 1994 to December 2015 and provides ocean current velocity components, u and v, in eastward and northward directions, respectively with a spatial resolution of 1/12° × 1/12° and temporal resolution of three hours.
Fog: North American Regional Reanalysis (NARR) hindcast model	Fog occurrence estimated using the horizontal visibility data. The visibility data in NARR are available at a 0.3° (approximately 32 km) spatial resolution and at a three-hourly temporal frequency. Available data covers the period from January 1979 to August 2021.
Sea Surface Temperature: ERA5 Reanalysis data	Data available from 1979 to present having a 0.25° (approximately 28 km) spatial resolution, and a one-hourly temporal resolution.
Air Temperature: ERA5 Reanalysis data	Data available from 1979 to present at 2 m height and having a 0.25° (approximately 28 km) spatial resolution, and a one-hourly temporal resolution.
Sea Ice: Canadian Ice Service (CIS)	Data within the CIS archives are available in two formats: weekly regional charts and daily charts, depending on location and year.
Icing: physics-based model	Calculated using the following inputs from given sources: sea surface temperature (ERA5 dataset), 10 m height wind speed (ERA5 dataset), 2 m height air temperature (ERA5 dataset), sea ice concentration (ERA5 dataset), precipitation type (ERA5 dataset), and sea surface salinity (Copernicus Marine Environment Monitoring Service dataset).
Bathymetry: General Bathymetric Chart of the Oceans	A global 30 arc-second grid largely generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data.

Fuglem et al. [1] describe the characterization of wind, waves, currents, and sea ice conditions for the 17 locations shown in Figure 1. In that study, wind speed and significant wave height date were taken from the MSC50 [5]. Ocean current data were extracted from the Global Ocean Physics Analysis and the Hybrid Coordinate Ocean Model (HYCOM). Sea ice data were extracted from the Canadian Ice Service daily and weekly sea ice charts.

4.2 Estimating Icing Accretion and Corresponding Downtime

Wind turbine icing can impede power

generation efficiency by altering the aerodynamic profile of the blades, damage turbine blades in extreme ice build-up scenarios, and can present hazards to personnel in their vicinity due to ice falling off the turbine blades. For floating OWTs, ice build-up can additionally create balance issues. The rate of ice build-up due to super-cooled sea spray freezing on contact with the turbines is a function of the air and sea surface temperatures, the wind speed, and the saltwater freezing point (e.g., see [6]). When precipitation icing occurs, the rate of ice accretion on turbine blades is a function of the wind speed, the liquid water content of the precipitation, the mean droplet size, the fraction of the precipitation that freezes, and the efficiency with which the turbine blades collect the freezing precipitation. In the present work, the rate of precipitation icing on wind turbines is not modelled as an explicit function of air temperature, as it occurs only due to freezing rain or wet snow when air temperatures are typically 0-3°C (e.g., see [7]).

Icing was modelled on a wind turbine at Site 10. Hourly data were acquired from the ERA5 global reanalysis (see [8]) for wind velocity, 2 m air and sea surface temperature, sea ice concentration, and precipitation type for 2003-2024 (22 years). An icing event was defined by a minimum threshold of 0.7 cm per hour of ice accretion on a turbine blade, which is the minimum icing rate for “moderate” icing according to [6], [9], [10]. Figure 3 shows the distribution, cumulative probability, and exceedance probabilities for icing event total accretions modelled for a wind turbine blade in the 6 o’clock position at 50 m above the sea surface. At this height, the blade tip reaches within the sea spray icing zone, which is assumed to extend to 60 m height [11], with sea spray icing rate decreasing exponentially with height. Ice accretion due to precipitation can occur anywhere on the turbine structure. Figure 4 shows the distribution of icing event durations in hours (with a Weibull curve fit), which is assumed to correspond with operational downtime. Over 2003-2024, an average of around 10 icing events per year were modelled (Figure 3 and Figure 4).

The extreme values of the total icing event accretion thicknesses for each section of the turbine structure were determined for the 1, 5, 10, 50, and 100-year return periods (see Table 3). First, the annual maximum icing event accretion was determined for each year. The probabilities (P_R) for each return period, R, were calculated according to:

$$P_R = 1 - \frac{1}{R} \tag{1}$$

where extreme values for each return period were then determined from an inverse Weibull cumulative distribution function.

The results in Figure 3, Figure 4, and Table 3 show that icing is not severe at Site 10, with 50% of events lasting less than two days with ice accretion less than 2 cm on the blade tip in the sea spray zone. In this region, icing prevention and mitigation methods such as using hydrophobic paint on the blades may reduce icing downtime further.

5. GEOTECHNICAL CONSIDERATIONS

As noted earlier, the Atlantic Canada Region has considerable geotechnical variability

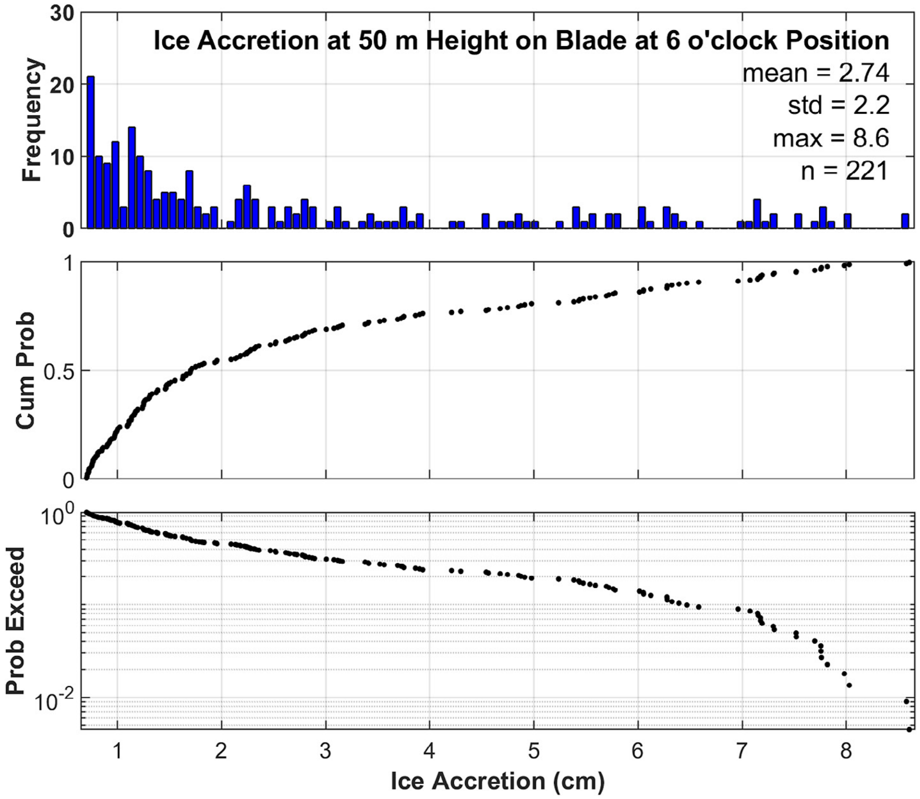


Figure 3: Modelled icing event total accretion.

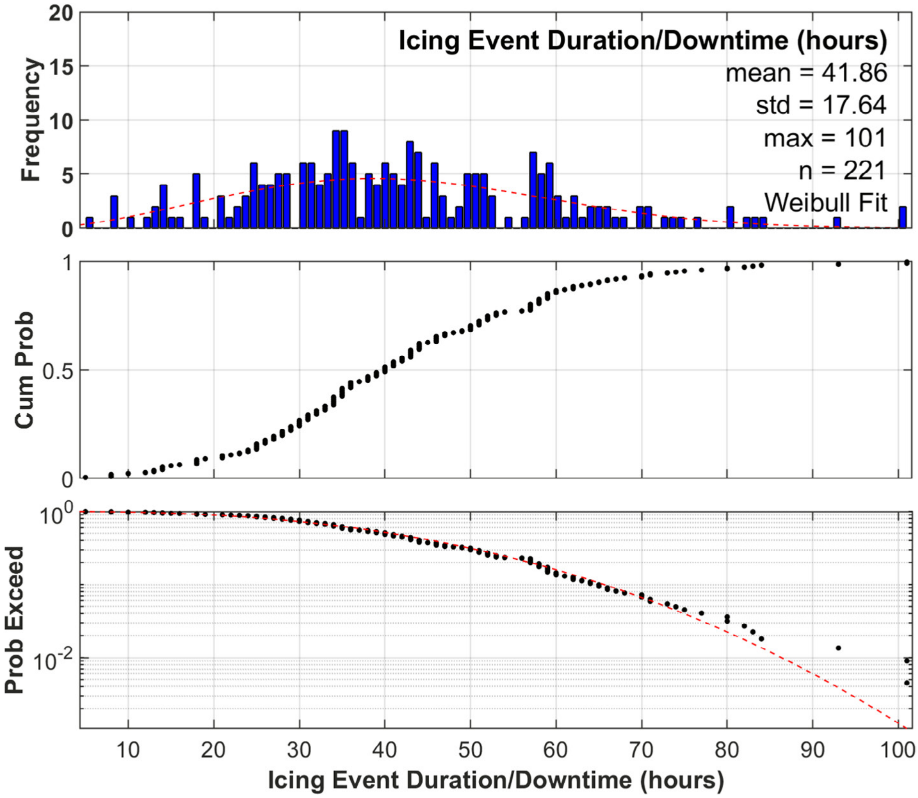


Figure 4: Modelled icing event operational downtime.

Table 3: Estimated icing event downtime (hours) by return period.

	Extreme Value Return Period (Years)				
	1	**5**	**10**	**50**	**100**
Downtime Hours	0	86	91	100	103

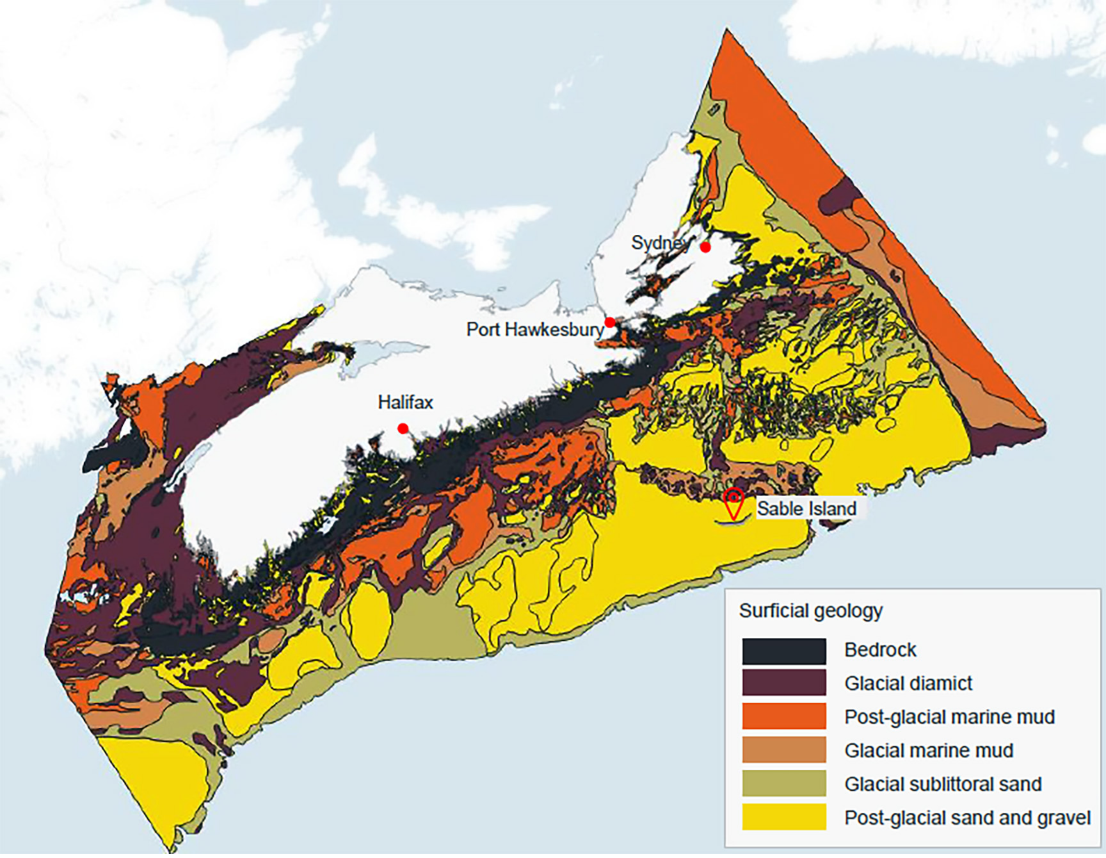


Figure 5: Surficial geology of the Scotian Shelf Bioregion; offshore Nova Scotia and New Brunswick, Canada; [13] after [14].

including post-glacial sand and gravel, glaciomarine mud, post-glacial marine mud, glacial till, and bedrock as illustrated in Figure 5. Offshore wind development areas lie within a region mapped as post-glacial sand or gravel, which is the same surficial geological unit that characterizes Sable Island. Borehole logs from the Sable Island area [12] illustrate this geological unit as being dominated by granular material, fine to medium sand, and sand-gravel mixtures with limited fines. This geological unit occurs across the region, and its thickness depends on location. On the outer banks, post glacial sand and gravel forms thick deposits (>20 m), whereas on the inner shelf, it appears as thin surface layers (<1 m) or patchy deeper accumulation (>10 m). The surficial geological maps provide confidence in the material type, a granular cohesionless sand-gravel mixture, but do not indicate how thick this unit is. Therefore, site-specific Cone Penetration Test (CPT) or borehole data are required for development.

The typical characteristics of post-glacial sand or gravel are consistent with the behaviour of dense sand. Post glacial sand and gravel are generally described as well drained, non-cohesive, and frictional, with unit weights on the order of 15.7 to 19.6 kN/m^3 and friction angles ranging from 36° to 45°. Material of this kind allows for efficient pile installation, as they provide predictable drivability and reduced risk of premature refusal compared with cohesive or variable seabeds. Once installed, monopiles embedded in such soils exhibit high lateral stiffness and reliable resistance to cyclic loading, owing to the frictional nature of the sand-gravel matrix and its tendency to mobilize strong passive resistance under lateral displacement. Taken together, these geological characteristics suggest that the selected region offers favourable geotechnical conditions for monopile foundations.

In contrast, post-glacial marine muds typically exhibit very low undrained shear strength (approximately 1-6 kPa), resulting in low lateral resistance and excessive lateral displacements for large diameter monopiles [12]. These deposits are, therefore, generally unsuitable for monopile foundations. Consequently, monopile feasibility on the Atlantic shelf is governed primarily by local soil conditions, with post-glacial sand and gravel representing the preferred founding material.

5.1 Soil-Pile Modelling

Given the dominance of post-glacial sand and gravel within the selected offshore wind energy area, lateral soil-pile interaction for the monopile foundation was characterized using the sand p-y method described in API RP 2GEO. This methodology is widely adopted for representing the non-linear lateral resistance of cohesionless soils and provides a consistent basis for feasibility-level analyses using representative soil parameters. In this formulation, the soil reaction at any depth is governed by an ultimate lateral resistance dependent on depth, effective unit weight, and friction angle. The resulting non-linear cyclic p-y curves for dense sand are shown in Figure 6.

5.2 Linearization of p-y Curves for Dynamic Soil-Structure Interaction Analysis

The cyclic p-y curves were converted into an equivalent linear soil-structure interaction representation for use in OpenFAST. As OpenFAST requires the foundation to be defined through a linear stiffness matrix at the mudline, the cyclic p-y relationships were linearized using a secant stiffness evaluated at a small reference displacement equal to 1% of the pile diameter. The resulting depth-dependent stiffness profile was applied to a beam-on-elastic-foundation model of the embedded monopile and subsequently condensed to obtain an equivalent 6×6 foundation stiffness matrix. This approach is widely used to represent monopile foundations in dynamic OWT analyses [15], [16].

5.3 Mooring Considerations for Varying Soil Types

For floating structures, mooring system performance in different soil types need consideration and verification. Table 4 highlights mooring types, soil preference, load resistance orientation, and qualifying comments. As highlighted above, soil conditions and depth vary considerably across

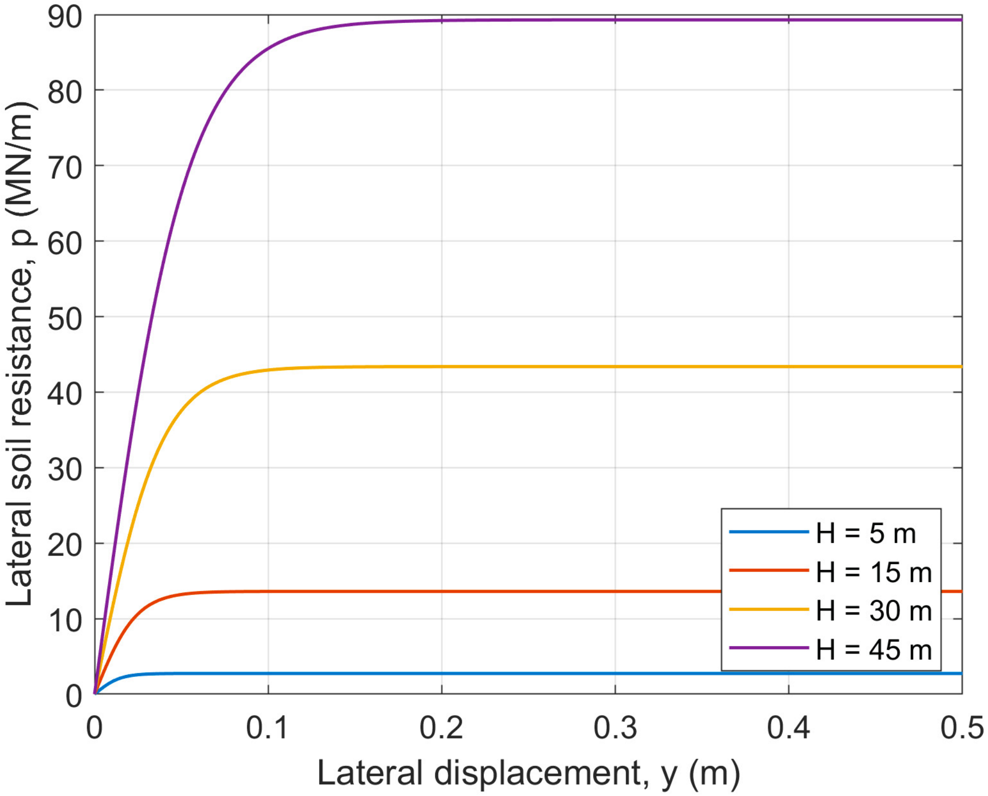
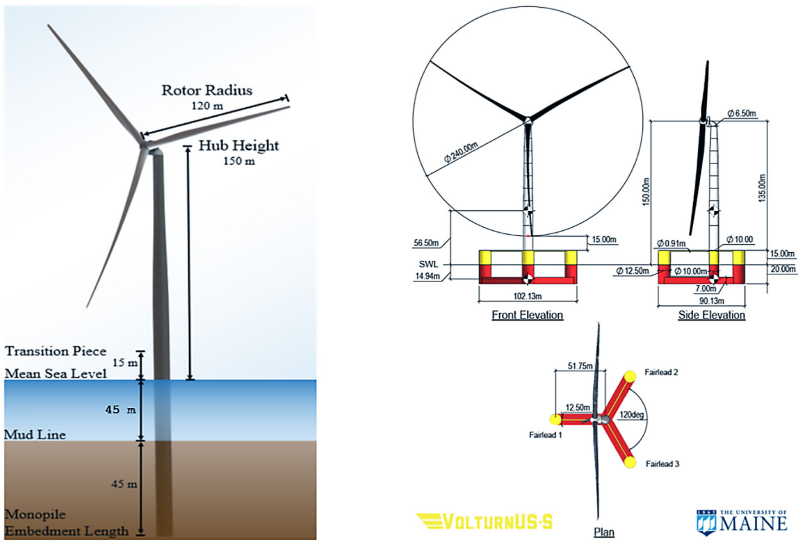


Figure 6: Cyclic p-y curves for monopile in dense sand.

Table 4: List of anchor types and applicability.

Anchor type	Soil preference	Typical load orientation	Comments
Drag embedment anchor	Soft to medium sand, silt	Primarily horizontal	Simple, inexpensive; high horizontal capacity; vertical capacity low.
Vertically loaded anchor	Soft clay, silt, some sand	Vertical (and horizontal)	Can be installed with suction caisson; good vertical capacity; resists horizontal loads.
Suction caisson	Soft clay, silty clay	Both vertical and horizontal	Excellent vertical capacity; height greater than width; installation requires specialized vessel.
Suction bucket	Soft clay or mud	Horizontal	Excellent horizontal capacity; width greater than height; simpler installation than suction caisson.
Driven pile anchor	Soft to medium clay, sand, silt	Both horizontal and vertical	Fast installation in suitable soils; well-understood capacity; limited in hard soils or rock; moderate cost.
Drilled and grouted pile anchor	Stiff clay, sand, gravel, rock	Both horizontal and vertical	Applicable in hard soils; high capacity; slow and expensive installation; specialized rig required.
Gravity base anchor	Any	Horizontal and vertical	Relies on weight of structure; requires flat seabed; heavy in deep water; installation cost high.



(a) IEA Wind 15-Megawatt Offshore Reference Wind Turbine

(b) UMaine VolturnUS-S Reference Platform

Figure 7: Monopile and semi-submersible platforms analyzed in this study.

the region. Depending on the spatial arrangement and size of a farm, different mooring systems may be required, or systems that can perform in different conditions may be more desirable. This highlights the importance of good geotechnical data across a development region.

6. EXAMPLE APPLICATION

6.1 Approach

OpenFAST is used to evaluate multiple DLCs defining production and parked design situations for two 15 MW OWTs (one with a monopile foundation and the other supported by a semi-submersible platform). The simulations are conducted using OpenFAST v3.5.3, an open-source, coupled aero-hydro-servo-elastic analysis tool developed and maintained by the US National Renewable Energy Laboratory (NREL) [17]. Atmospheric turbulence is represented using wind fields generated with TurbSim, NREL's stochastic wind field simulator [18]. Together, these tools provide a comprehensive framework for assessing the dynamic response of OWTs subjected to combined environmental loading, including wind, wave, and ice effects.

The wind turbine model is based on the IEA Wind TCP 15 MW reference turbine, classified as IEC 61400-3-1 Class IB (Figure 7, left). The turbine has a rotor diameter of 240 m and a hub height of 150 m. Two distinct support structures are considered. The first is a 10 m-diameter monopile installed in 45 m water depth; additional details of the monopile model are provided in [19]. The monopile is assumed to be rigid at the mudline.

The second is the UMaine VolturnUS-S semi-submersible platform, a concrete-based floating foundation developed by the University of Maine's Advanced Structures and Composites Center [20] (Figure 7, right). Both support structures are coupled to the same IEA Wind TCP 15 MW reference turbine.

Table 5: Summary of OpenFAST cases.

Case No.	Description	Design Situation	DLC	Ws (m/s)	Hs (m)	Tp (s)	Current Speed (m/s)	Ice Thick (m)	Ref Ice Str. (MPa)	Monopile base at mudline
1	Monopile; production	Production	1.1	15	2.22	7.05	0.37	N/A	N/A	Rigid
2		Production	1.1	10	1.25	5.54	0.37	N/A	N/A	Rigid
3		Production	1.1	20	3.34	8.30	0.37	N/A	N/A	Rigid
4	Monopile; production, with level ice	Production	1.1	15	N/A	N/A	0.37	1	1	Rigid
5		Production	1.1	15	N/A	N/A	0.37	0.5	1	Rigid
6		Production	1.1	15	N/A	N/A	0.37	1.5	1	Rigid
7	Monopile; production, accounting for soil stiffness	Production	1.1	15	2.22	7.05	0.37	N/A	N/A	Flexible
8		Production	1.1	15	1.25	5.54	0.37	N/A	N/A	Flexible
9		Production	1.1	15	1.25	5.54	0.37	N/A	N/A	Flexible
9.1		Production	1.1	15	1.25	5.54	0.37	N/A	N/A	Flexible
10	Monopile; parked mode* and hurricane check	Parked/stand.	6.1	43	9.1	12.3	0.67	N/A	N/A	Rigid
11		Parked/Idling	6.1	43	6.7	10.3	0.67	N/A	N/A	Rigid
12		Parked/stand.	I1	55	10.3	12	0.67	N/A	N/A	Rigid
13		Parked/Idling	I1	55	10.3	12	0.67	N/A	N/A	Rigid
101	Semi; production	Production	1.1	15	2.22	7.05	0.37	N/A	N/A	N/A
102		Production	1.1	10	1.25	5.54	0.37	N/A	N/A	N/A
103		Production	1.1	20	3.34	8.30	0.37	N/A	N/A	N/A

*Two parked modes are considered in accordance with IEC 61400 series: (1) idling (parked with blades free to rotate, typically not producing power), and (2) standstill (parked with the rotor locked or secured in position).

In total, 17 simulation cases are defined for analysis in OpenFAST: 14 cases for the monopile and three cases for the semi-submersible platform. Cases 1 to 3 represent production mode at wind speeds of 10, 15, and 20 m/s. Cases 4 to 6 introduce ice loads from level ice using the IceFloe module (see [21] for details). Cases 7 to 9.1 consider varying soil strength and account for a flexible monopile. In Cases 10 and 11, the monopile is in a parked condition under a 50-year wind speed, while Cases 12 and 13 represent hurricane conditions with 500-year wind speeds. Cases 1 to 3 and 10 to 13 are also repeated for a semi-submersible platform. A complete summary of all cases is provided in Table 5.

6.2 Monopile Results

Fourteen OpenFAST simulations were performed for the wind turbine supported by the monopile foundation situated in 45 m water depth. As recommended in the IEC 61400 series, multiple simulations with unique random seeds are run for 600 seconds to capture the relevant stochastic variability of wind and wave loading. Here, only one simulation has been done for each case for expediency. Table 6 provides 90th percentile values for a selection of OpenFAST output parameters. Note these results do not include the normal/abnormal partial safety factors described in the IEC 64100 series.

For the monopile production (Cases 1-3), increasing wind speed from 10 to 20 m/s increases aerodynamic and structural loading, with both fore-aft and lateral nacelle accelerations increasing slightly, and tower top

Table 6: Summary of 90th percentile output parameters from OpenFAST simulations.

No.	Ice, Fx	Nac. Accel.		Rot. Thrust	TwTip Disp.	Tower Base				Mudline			
		X	Y			Fx	Fy	Mx	My	Fx	Fy	Mx	My
	MN	m/s^2	m/s^2	MN	(m)	MN	MN	MN·m	MN·m	MN	MN	MN·m	MN·m
1	N/A	0.15	0.25	2.69	1.49	2.54	0.13	32.4	275	3.15	0.60	46.3	424
2	N/A	0.21	0.31	1.77	0.81	1.69	0.18	48.9	156	3.04	0.63	65.9	276
3	N/A	0.25	0.37	1.42	0.57	1.41	0.17	54.0	114	3.40	0.77	77.6	228
5	2.86	0.18	0.30	1.77	0.88	1.69	0.15	41.7	154	4.64	0.74	61.8	356
4	4.84	0.21	0.30	1.78	0.97	1.77	0.19	41.2	158	6.69	0.95	68.0	441
6	6.86	0.26	0.31	1.78	1.06	1.87	0.23	41.1	162	8.81	1.19	76.5	531
7	N/A	0.20	0.30	1.78	0.81	1.70	0.16	45.2	157	3.03	0.62	62.1	274
8	N/A	0.20	0.30	1.78	0.81	1.70	0.16	45.2	157	3.03	0.62	62.1	274
9	N/A	0.20	0.30	1.78	0.81	1.70	0.16	45.2	157	3.03	0.62	62.1	274
9.1	N/A	0.46	0.37	1.82	1.71	1.98	0.27	67.6	196	3.56	1.30	84.2	283
10	N/A	0.81	0.35	0.56	0.57	1.63	0.39	61.4	113	6.45	0.83	87.0	294
11	N/A	0.88	0.28	0.57	0.64	1.72	0.32	38.5	125	6.47	0.54	60.7	310
12	N/A	1.02	0.23	0.62	0.78	1.90	0.26	48.5	146	7.26	0.59	66.4	355
13	N/A	1.03	0.19	0.62	0.78	1.91	0.22	25.0	147	7.26	0.38	38.4	353

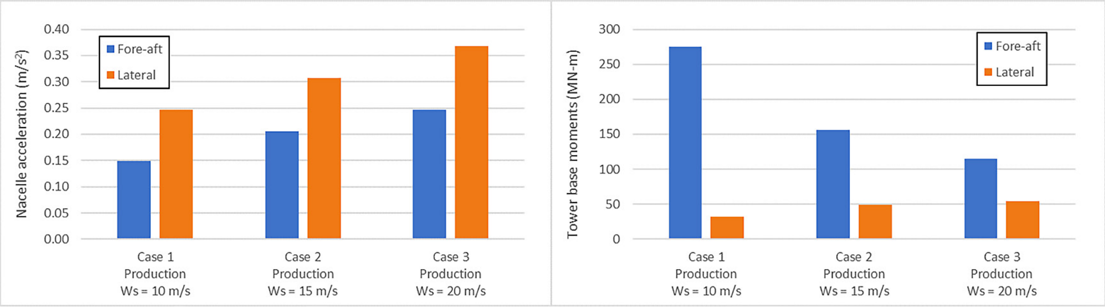


Figure 8: Nacelle acceleration and tower base moments for production cases.

fore-aft displacements decreasing (see Figure 8 and Table 6). Fore-aft tower-top motion and fore-aft loads decrease with wind speed due to blade pitch regulation by the controller.

When operating in production mode, the structure benefits from strong aerodynamic damping, which results in relatively low nacelle accelerations and tower motions. When the turbine transitions to parked conditions at higher wind speeds (Cases 10-13), the structural response changes, as the aero-dynamic damping is reduced or eliminated (Figure 9). Fore-aft nacelle accelerations increase significantly relative to production, reaching about 0.8-1.0 m/s^2, though these accelerations are less than the 0.3 G upper limit that is sometimes referenced. Lateral accelerations remain lower and comparable. Even under extreme winds and hurricanes, idling operation provides a small amount of aerodynamic damping to noticeably reduce lateral tower base and mudline loads compared with full standstill; fore-aft moments remain similar.

Introducing stochastic ice loads (Cases 4, 5, and 6) increases the fore-aft structural loading of the structure (see Figure 10). Fore-aft nacelle accelerations, tower top displacement, and tower base shear forces increase slightly compared to the equivalent production case (Case 1). Loads at the mudline show a more

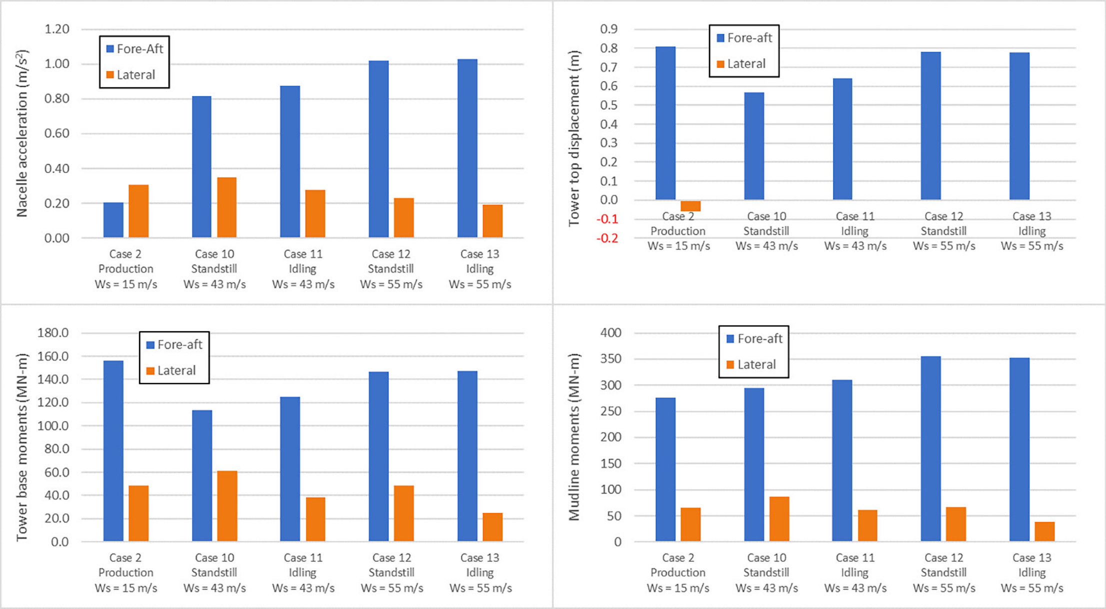


Figure 9: Comparison of production, idling, and standstill cases.

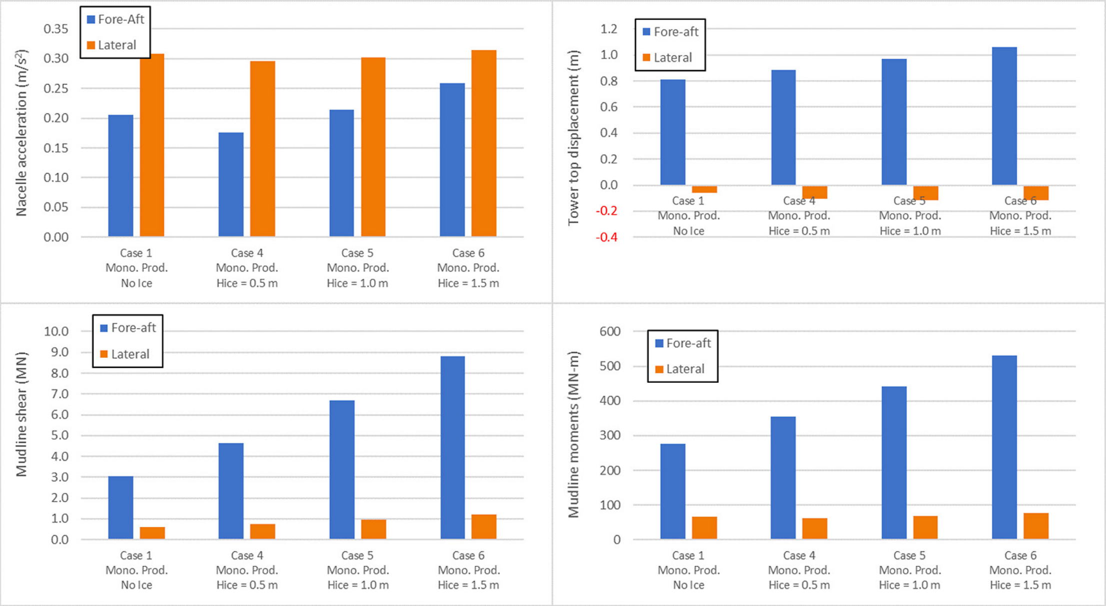


Figure 10: Comparison of different ice loads (thicknesses) for the monopile.

significant increase, especially in the fore-aft direction where loads for the case with the thickest (but less frequently observed) ice are nearly doubled those of the non-ice case. Overall, ice loading increases both tower-top motions and mudline loads, highlighting its effect on monopile structural response. In design, a probabilistic assessment of ice loads is needed to accurately capture the effects of the thickest, though least likely, ice interactions, and the effects of misaligned wind and ice directions.

In a previous study assessing a wind turbine supported by a monopile foundation [21], it

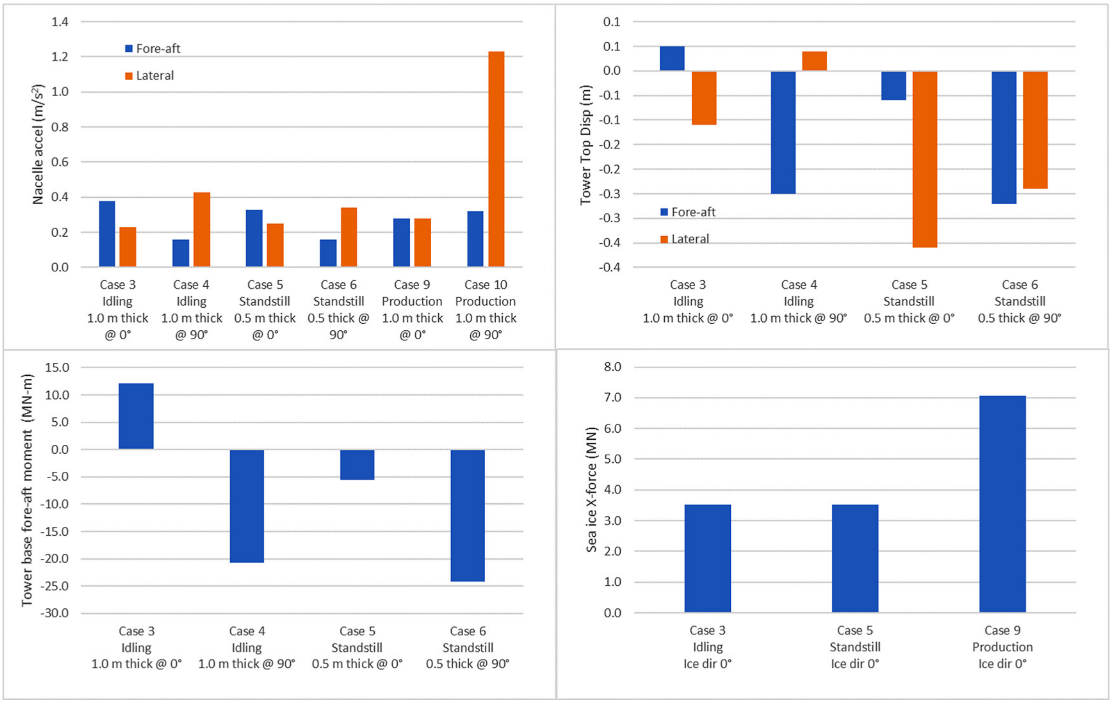


Figure 11: Comparison of sea ice results from [21]. Note the definition and numbering of cases in this table are based on Table 5 in [21] and are provided here to illustrate how ice drift direction impacts turbine response.

was shown that, for the parked cases, lateral ice loading, compared to inline ice loading, produced significant damping effects on fore-aft mudline moments and nacelle accelerations (see Figure 11). Tower base moments are considerably higher when ice moves at 90° relative to wind, as there is no aerodynamic damping. Further, nacelle accelerations are largest for production case when ice moves at 90° relative to the wind and damping on vibrations associated with random ice crushing is the smallest. Coupling these with a softer (vs. rigid) seabed will introduce different damping effects that will further influence forces, moments, and nacelle accelerations, which should be studied further. Different ice load models may need to be considered for the cases of ice-induced vibration and sloped structures.

For the monopile, soil stiffness will influence the structural response as illustrated in Figure 12. The equivalent 6×6 foundation stiffness matrix developed in Section 5.2 was based on post-glacial sand and gravel and, when introduced to the OpenFAST simulation, resulted in no changes to output parameters. Sensitivity cases, where the stiffness values were scaled by factors of 2 and 0.5, also showed no difference when compared to the base case stiffness results. One thought is that the base case stiffness matrix was very high (approaching "rigid" responses) and that factoring by 0.5 still resulted in a very high stiffness. Further, reducing the stiffness by a factor of 100 (Case 9.1) resulted in noticeable increases in tower motions and mudline shear forces. Nacelle accelerations increased significantly, with smaller increases in the tower top motions and mudline shear. This sensitivity analysis underscores the importance of collecting in-situ soil data and developing accurate modelling inputs.

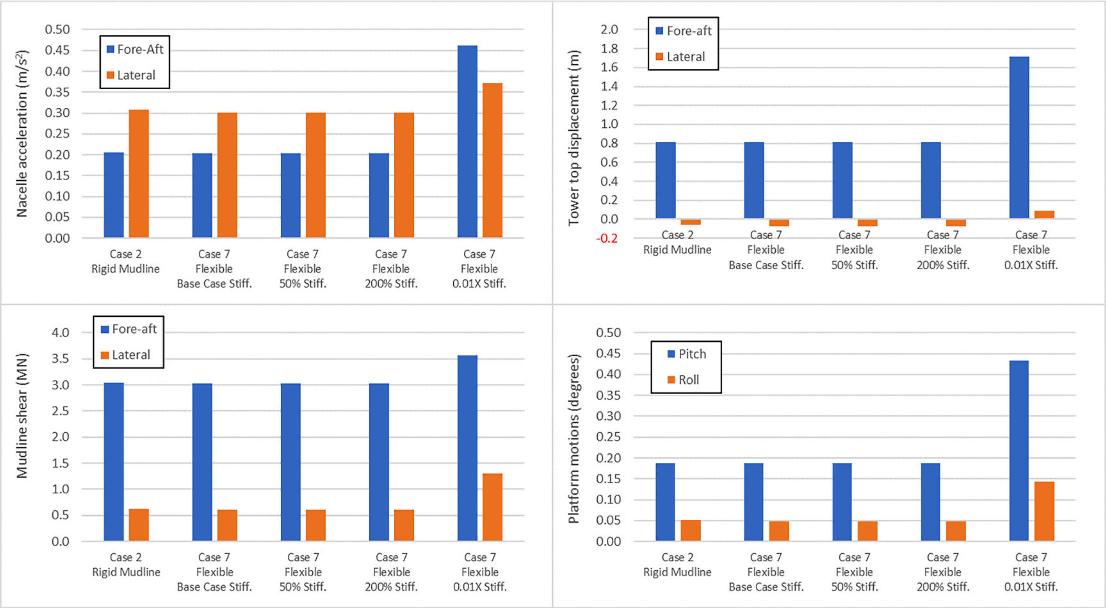


Figure 12: Comparison of various soil stiffness models for the monopile.

Table 7: Summary of 90th percentile output parameters from OpenFAST simulations.

No.	Nac. Accel		Rot Thr.	TwTip Disp.	Tower Base				Mooring Line 1		Platform	
	X	Y			Fx	Fy	Mx	My	Fair. Ten.	Anch. Ten.	Pitch	Roll
	m/s^2	m/s^2	MN	(m)	MN	MN	MN·m	MN·m	MN	MN	Deg.	Deg.
101	0.25	0.07	2.55	13.6	4.01	75.9	51.2	370	8.8	8.0	4.41	0.66
102	0.23	0.08	1.95	10.0	2.96	2.83	62.4	260	8.4	7.6	3.19	0.79
103	0.29	0.15	1.51	7.30	2.30	31.4	81.8	193	8.2	7.4	2.32	1.03

6.3 Semi-submersible Results

6.3.1 OpenFAST Results

Three production cases are analysed for the semi-submersible platform and 90th percentile values for a selection of parameters are presented in Table 7.

Structural loads and platform responses are notably different for the semi-submersible compared to the monopile; refer to Figure 13. The semi-submersible reduces lateral nacelle accelerations but has larger global motions, including a tower top displacement of about 7 to 14 m; fore-aft accelerations remain comparable. For the monopile, lateral nacelle accelerations are higher, while tower-top displacements remain relatively small, indicating high stiffness for the fixed monopile. With the much higher tower motions, the fore-aft tower base shear and moments for the semi-submersible are much higher compared to the monopile.

6.3.2 Sea Ice Loads

For this study, an analysis of sea ice loads on the semi-submersible was not carried out but should be in subsequent studies as the additional dynamics and damping effects from sea ice will influence structural forces and moments, mooring tensions, platform motions, blade deflections, and nacelle accelerations.

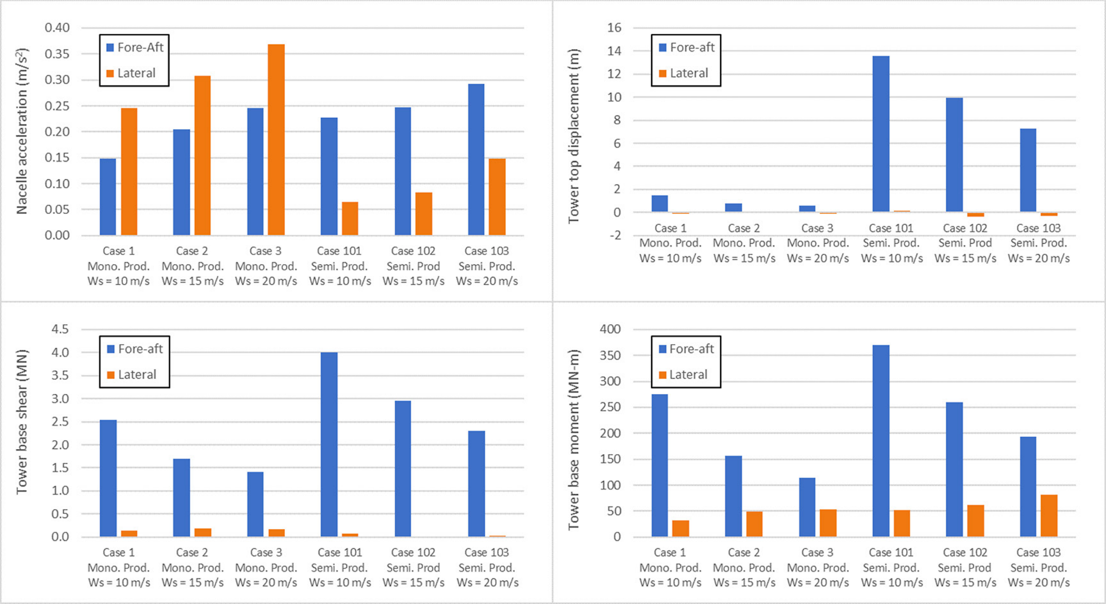


Figure 13: Comparison of tower motions and loading for the monopile and the semi-submersible.

The interaction of floes with a flexible moored structure introduces added complexity where pack ice floe diameter, ice driving forces, ice failure forces and dynamics, as well as mooring stiffness (and flexibility) all need to be considered. As wind, waves, and currents push an ice floe, tension increases in the mooring until the force at which ice failure can occur on the structure is reached. Then the floater will crush forward into the floe. This distance is limited and continues until tension drops, the force to fail the ice drops, and only driving forces remain. This cyclic process continues until the floe has moved past the platform. Two important items are noted. The IEC standard requires 600 seconds of simulation to verify whether lock-in frequencies occur, which will be limited by cyclic process noted above. Also, the diameter of floes further to the south will continually reduce as higher average water temperatures weaken the ice and wave action breaks them up, limiting the amount of distance available for floe crushing (and dynamics) to occur. Coupled with low annual occurrence in most areas, exposure will be reduced, further mitigating sea ice effects.

6.3.3 FEPLA Anchoring System

In this study, a Flexible Embedded Plate Anchor (FEPLA) was considered as a mooring option in dense sand. This included physical verification testing of the capacity of a 7.6 × 3 m FEPLA (see Figure 14) at different depths. This was part of a centrifuge-based demonstration test studying the performance of a FEPLA under different embedment depths.

Suction Embedded Plate Anchors (SEPLA) have been proven for application in soft clays with the advantages being relatively low cost and having a high installation positioning accuracy. As the offshore wind industry continues to expand, there is a growing need for the evolution of mooring designs to

Figure 14: Illustration of plate anchor and the Acteon Flexible Embedded Plate Anchor (FEPLA) system.

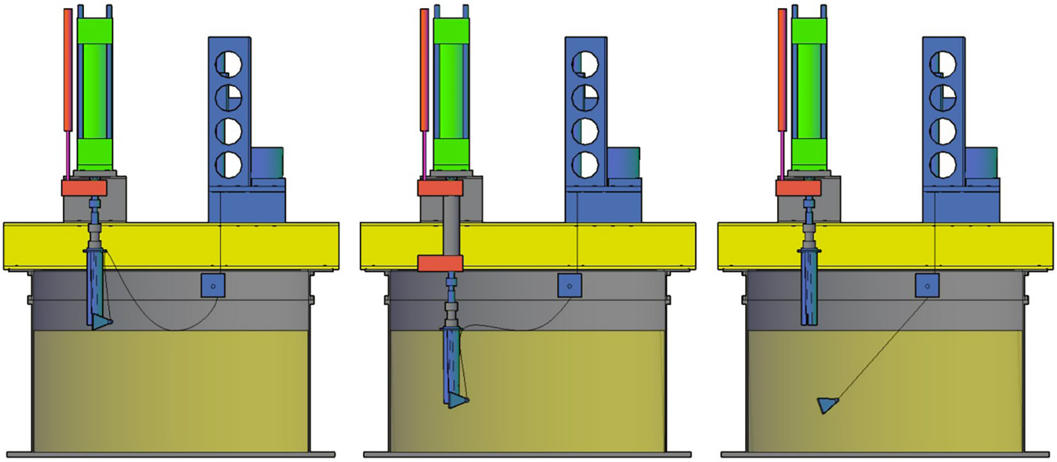


Figure 15: Illustration of centrifuge testing of the Acteon Flexible Embedded Plate Anchor (FEPLA) including installation and pulling.

provide even more effective, accurate, and cost-efficient alternatives. The FEPLA offers several advantages over traditional anchors, including deployment in shallow waters, stronger seabeds, and close proximity to other anchors. It has a hybrid embedment method that combines vibro hammering and impact hammering.

A geotechnical centrifuge test was carried out on a scaled FEPLA in saturated dense silica sand. A 1/60th scale centrifuge model of the FEPLA was manufactured (see Figure 15). The soil sample was prepared using air pluviated silica sand simulating a common shallow shelf soil. The model testbed was vacuum water saturated. A cone test was completed demonstrating a repeatable and consistent relative density (Dr = 85%).

The anchor was installed at a low G level at installation depths of 2 and 3 times the fluke height ($H = 3$ m). When at the target G level, the anchor was pulled to soil failure. Measuring that capacity at varied installation depths was the goal of this demonstration test. Full scale ultimate holding capacity of 12.5 MN at $3H$ depth and 6.3 MN at $2H$ depth was measured. An Abaqus finite element model of the centrifuge test was carried out modelling both the installation and pullout. Loads in the Abaqus model compared well, within 6%, of the centrifuge model results.

Based on these results, the expected FEPLA installation depth for the example floating turbine assessed in the previous section with peak tension of 8 MN would be just over $2H$ or 6-8 m depth.

Future testing could be completed to study additional prototype geometries, push or hammer installation, pull velocities, and pull angles. Additional studies could be completed considering cyclic loading, displacement under sustained tension and anchor tilt. Building on SEPLA technology, these new anchors can be precisely positioned without the use of suction, making them suitable for the dense clustering needed in offshore wind installations in sand and shallow waters.

7. CONCLUSION AND RECOMMENDATIONS

The findings of this study highlight some of the unique aspects of offshore wind development in Atlantic Canada. Conditions vary significantly across the region including water depths, soil types, exposure to extratropical storms, weakened hurricanes, icing, and, in more northerly regions, seasonal sea ice. Structures selected will be optimized based on the local conditions, and, in some cases, different structure types and different mooring systems may be required within the same development.

The analyses in this paper emphasize the critical role of turbine operational mode and the effect on structural loading, especially under extreme wind conditions. Idling provides aerodynamic damping, which reduces extreme motions but introduces higher thrust and nacelle accelerations. Production based forces and moments are larger than parked or idle modes.

As discussed in [1], hurricanes can reach Atlantic Canada but are often diminished in strength by the time they arrive. IEC 61400-1 recommends performing a robustness check for hurricanes using the 500-year wind speed combined with a partial safety factor of 1.0, compared to a partial safety factor of 1.25 applied for production DLCs. For example, from Table 6, the production loads (e.g., Cases 1, 2, and 3) factored by 1.25 are similar to the hurricane generated loads factored by 1.0 (Cases 12 and 13). This confirms the use of idling (free rotor) control as an effective load mitigation strategy during high wind events such as hurricanes.

Canada is presently adopting the IEC 61400-3-1 standard for fixed wind turbine structures with deviations, including reference to methods for determining ice loads referenced in ISO 19906. The IEC 61400-3-2 standard for floating wind turbine structures has not yet been adopted in Canada; it is of note that this standard defers to ISO 19906 for ice loads. While ISO 19906 generally has methods for determining design ice loads, the methods were developed for oil and gas drilling and production platforms and typically define fixed design loads. Further guidance may be needed on developing load time series and modelling coupled wind and ice load effects, with added emphasis on intermittent crushing and ice-induced vibrations.

It is important to initiate enhanced measurements of wind, wave, current, and ice occurrence and mobility at locations where wind power production may be considered to accurately characterize conditions and avoid overly conservative assumptions. In many regions in Atlantic Canada, ice floes are typically small, and floes with sufficient diameter to achieve lock-in failure frequency vibrations are unlikely – unlike Baltic conditions where fixed installations are being designed for ice loading. Developing improved modelling techniques to assess the potential influence of wind turbine arrays on sea ice conditions and movements is equally important, particularly for production mode.

Site-specific detailed geotechnical investigations will be essential to quantify stratigraphy, density variability, friction angle, stiffness profiles, and the presence of gravel or shell layers that may influence drivability or lateral capacity. CPTs, boreholes, and laboratory characterization will allow site-specific soil models to be developed and will refine estimates of drained strength and deformation behaviour in accordance with offshore design standards. Such data will also enable more accurate soil-structure interaction modelling, which is required for final monopile sizing and verification of lateral performance under operational and extreme load conditions. While not specifically addressed in this paper, certifying mooring systems for certain applications requires an in-situ pull test to verify capacity. In the case of a large offshore wind energy development with hundreds of moored turbines, this approach of verification is not practical, and alternative approaches will be required. These may include more accurate seabed/soil profiling coupled with physical testing (e.g., centrifuge) and calibrated numerical finite element modelling.

Finally, in accordance with the IEC 61400 series, the design of a single turbine is typically based on extreme metocean conditions with a 50-year return period. However, as the size of farms increase, the design philosophy may need to move from a "per turbine" design to an overall wind farm design where the consequence of the failure of one or more turbines is considered. This may result in the need to design to a higher reliability target.

ACKNOWLEDGMENT

The authors gratefully acknowledge funding from the Department of Industry, Environment and Technology, Government of Newfoundland and Labrador, for supporting the development of the drive actuator used to install the FEPLAs in the centrifuge. The authors also acknowledge the collaborative support of Acteon in providing dimensions of a FEPLA as well as technical support for performance modelling.

Authors' Declaration

- 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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