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Review of Approaches for Modelling Sea and Lake Ice Loads on Offshore Wind Turbines

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ABSTRACT

Offshore wind turbines must be built to withstand harsh marine conditions, including significant wind and wave loads. To be economical, the structures are designed to be relatively light, and as a result, the loads can result in significant non-linear effects, coupling between responses of the turbine and supporting structure, and susceptibility to fatigue. In regions such as the Baltic Sea, the Bohai Sea, the Great Lakes, and offshore Eastern Canada, sea or lake ice is present in winter. Ice in higher concentrations suppresses waves but results in direct ice loads on the structure. Global and local ice loads need to be assessed in such cases.

This paper reviews design requirements and models for global ice loads for offshore wind turbines. Focus is given to the structure types and ice conditions that might be encountered off Eastern Canada or in the Great Lakes.

KEYWORDS: Offshore Wind Turbines, Sea Ice, Lake Ice, Ice Interaction Models, Design Loads and Effects

BACKGROUND

Canada holds significant potential for offshore wind power development, but much of its offshore area is subject to seasonal sea or lake ice, and even icebergs in certain regions. Two regions of interest are the Great Lakes and Atlantic Canada (Figure 1). The Great Lakes have milder ice conditions, but wind development in the Canadian part of the Great Lakes is presently under a moratorium. Atlantic Canada has a large variation in ice conditions, ranging from essentially ice-free to the west of Nova Scotia and south of Newfoundland, to heavy first-year ice with icebergs and trace amounts of old ice off Labrador.

The Great Lakes are relatively warm, with thinner ice. Because of the absence of brine, freshwater ice is stronger than sea ice. The ice season and thickness depend on the water depth and local climate. Lake Ontario, which is furthest to the east, is over 200 m deep in parts. It is mostly ice-free, with maximum ice cover ranging from less than 10 to 65%. Ice thickness can reach 0.6 m in bays. Lake Erie is relatively shallow, with water depths ranging from 30 m in the western part to twice this depth in the eastern basin. It therefore freezes and melts relatively quickly. The maximum cover ranges from 8% to 100%. The ice thickness can reach 0.45 m in bays, and pressure ridges up to 20 m in depth can occur. Lake Huron has an average depth of 60 m and a maximum depth of 230 m. The annual maximum cover ranges from 25% to 98%, ice thickness can reach 0.75 m in bays, and pressure ridges up to 18 m in depth can occur. Lake Superior has an average depth of around 150 m and a maximum depth of around 400 m. The annual maximum cover ranges from 10% to 98%, thickness can reach 0.85 m in bays, and pressure ridges up to 25 m in depth can form. Several studies have been conducted in the U.S.

on wind development in Lakes Erie and Ontario, but focus in the US is on developments off the Atlantic coast, given reasons such as the absence of sea ice and better ports and access to installation vessels (D'Agostino, 2025, Pollack, 2023, NYSERDA, 2022).

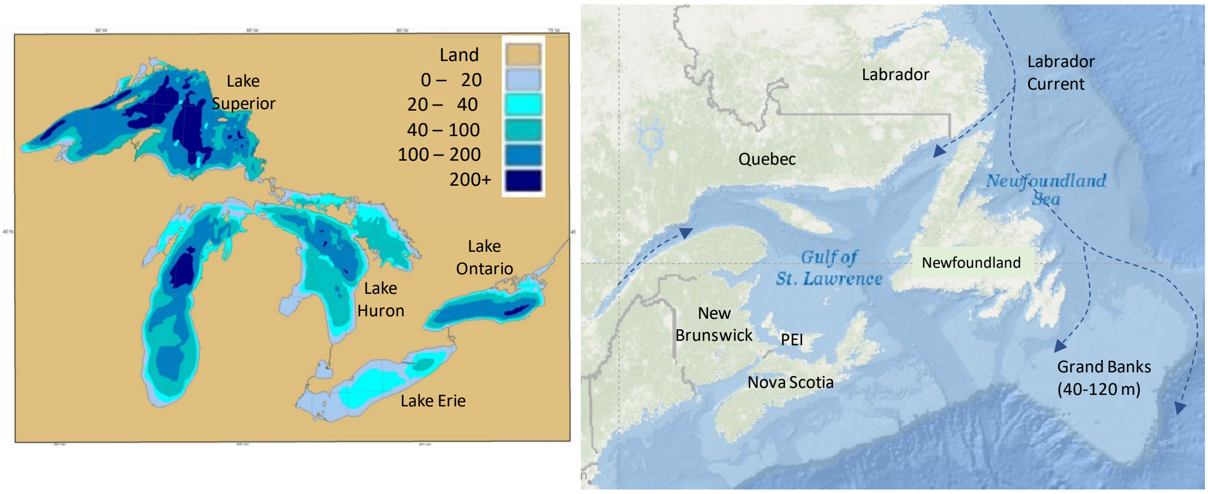

Figure 1. Regions in southern Canada with both significant wind potential and moderate sea ice conditions (Left: Great Lakes with bathymetry (m) shown; Right: Atlantic Canada)

The Labrador Sea experiences heavy first-year sea ice, trace amounts of multi-year ice and icebergs that drift with the Labrador current from further north. The heaviest ice conditions are close to the Labrador shore. The concentration of sea ice and the areal density of icebergs generally decrease as one moves further south. On reaching Newfoundland, the Labrador current swings east and then splits, with a portion going south along Newfoundland's east coast and the majority continuing east across the northern boundary of the Grand Banks before turning south again. At these latitudes, the ice is spread over a greater area than off Labrador, and often is considered marginal, with waves breaking the ice into small floes. There are currently both fixed and floating oil production platforms on the northern Grand Banks, and consideration has been given to the use of floating wind turbines to provide them with power.

The southern Grand Banks have lower exposure to icebergs and sea ice. It has extensive areas with water depth in the 60 m to 80 m range that are outside of major fishing grounds and shipping lanes and have very strong winds (with a potential capacity of up to 100 GW using wind turbines, King et al., 2025). While development at these water depths is challenging, as it is too deep for monopiles and not deep enough for floaters, alternative designs, such as jacket structures or extended monopiles supported with guy wires, have potential if proven cost-effective.

The Gulf of St. Lawrence predominantly has first-year sea ice, although icebergs and old ice sometimes enter the northern region through the Strait of Belle Isle. The concentrations and thickness of first-year sea vary considerably but may exceed 1.5 m in the northern part of the gulf. Fuglem et al. (2024) provide an overview of wind, wave and ice conditions across the region. Initial offshore wind development will likely occur in those areas with more limited sea ice. Approximately two-thirds of the Gulf has water depth exceeding 100 m and would require floating platforms.

While Canada has considerable experience designing ports, dams, and bottom-fixed and floating offshore oil and gas platforms to withstand ice loads, there has been limited involvement in the design of offshore wind turbines. The objectives of this paper are as follows.

- Review design criteria for ice load on offshore wind turbines.
- Review approaches and models for simulating ice loads on offshore wind turbine support structures.
- Provide a simple example for the case of an individual floe impacting a monopile wind turbine using the OpenFAST software to illustrate some of the challenges.
- Identify gaps regarding available environmental and ice data, and ice loading strategies for modelling offshore wind turbines in Canadian regions with ice.

APPLICABLE STANDARDS AND DESIGN CRITERIA

The IEC 61400-3-1 standard for bottom-fixed offshore wind turbines has been adopted in Canada with deviations. IEC 61400-3-2 for floating structures has not yet been considered for adoption. Table 2 of IEC 61400-3-1 outlines 'design situations' and 'design load cases'. The design situations include 'power production', 'parked', 'production with fault', etc. Design load cases are defined for both ultimate and fatigue limit states. Ultimate limit states are classified as 'normal' or 'abnormal' depending on their frequency, with the classification 'normal' typically having a higher partial load factor than 'abnormal', which is less frequent.

Because wind turbine systems are highly non-linear and fatigue loads are important, the standard requires analysis to establish the system's response to load time series where these are stochastic. The period of load data must be long enough to ensure statistical reliability of the required characteristic load effects. A minimum of six ten-minute simulations (based on different random number sequences) or a one-hour simulation is recommended. Increased simulation times are specified for certain design load cases with higher variance. The maximum load effects for each time series are determined, and extrapolation methods are used to determine the 50-year (or other extreme) load effect as needed.

Design ice load cases (IEC 61400-3-1 Table 3) are only specified for the 'power production' and 'parked' design scenarios. There are five design load cases for 'power production' (D1 through D5) and three for 'parked' design situations (D6 through D8). D1 and D2 are for fast ice, i.e., loads from temperature fluctuations (expansion) and water level variations, respectively. They should be evaluated based on wind speeds: 1) near the rated wind speed and 2) equal to the cut-out wind speed. D5 deals with vertical loads from spray ice and water level changes.

D4 and D7 consider fatigue with the 'power production' and 'parked' design situations, respectively. Both load cases reference the normal wind turbulence model and level ice thickness. For the 'power production' scenario, all wind speeds from cut-in to cut-out are considered and for the 'parked' scenario, all winds less than 0.7 times the reference (50-year) wind are considered. Wind speeds less than the cut-in speed are not referenced; the reasoning is not specified (is it assumed that the ice is not moving?). Only level ice interactions are referenced, and all ice thicknesses are to be considered. The selection of appropriate combinations of wind speed and ice thickness values for the simulations is left to the analyst.

D3 is for the 'power production' design situation and the ultimate limit state given moving level ice. The 50-year ice thickness is considered in conjunction with the normal turbulence model and wind speeds between cut-in and cut-out. For D3, D6 and D8, the possibility of differences in wind and ice direction, and different ice velocities need to be considered.

D6 is for the parked design situation and the ultimate limit state given pressure from hummocked ice and ice ridges. The extreme wind model and 1-year extreme wind speed are considered. Section D.4.6 indicates that static ice loads are considered, based on ice features with dimensions that would be exceeded once on average in 50 years. Reference is given to models for ridge loads, accounting for a consolidated layer, acting on vertical and sloped structures. In contrast, Croasdale and Allyn (2018) and Croasdale et al. (2019) developed dynamic load time series based on level ice with interspersed ridges for input for simulating loads on a monopile structure with a cone for reducing ice loads.

D8 is for the 'parked' design situation and the ultimate limit state given moving level ice. The 50-year ice thickness is considered in conjunction with the extreme wind model and the 1-year extreme wind speed.

In the Canadian deviations, it is suggested that the design load cases be made more general, i.e., rather than specifying 50-year ice thickness, on which horizontal loads are based, it is required that 50-year total ice loads be established. This allows for a broader range of ice scenarios, including loads on horizontal braces, which are not necessarily horizontal, and different ice features such as thick floes, ridges, rubble fields and glacial ice pieces. It is also suggested that load models in ISO 19906 can be used where appropriate.

The IEC 61400-3-2 standard for floaters provides little specific guidance on ice loads and references ISO 19906 for design ice cases. While ISO 19906 is quite thorough, it is geared more toward design loads for oil and gas production systems, and refinements specific to floating wind turbines may be required.

DNV has a fairly comprehensive set of standards and recommended design practices for offshore oil and gas platforms and wind farms. DNV-ST-0437 (Load and site conditions for wind turbines) outlines design situations and design load cases. The general approach is similar to that in IEC 61400-3-1, with design load cases specified for bottom-fixed and floating offshore wind turbines. Hendrikse (2024) points out some of the differences between IEC61400-3-1 and the 2021 version of DNV-ST-0437. There is now an updated 2024 version of DNV-ST-0437, where the design load cases have been modified and a new load case for ice ridges during power production has been added.

In the ISO 19906 standard (ISO 19906:2019), provision is made for active and passive ice management measures to alter the ice cover or deflect an ice feature and potentially reduce ice loads. For such measures to be acceptable, the protocols outlined in ISO 35104 (ISO 35104:2018) would need to be considered, and it is critical that the measures on which the design is based be maintained during operation.

The need for consideration of dynamic ice actions is highlighted in the different standards. For example, ISO 19906 indicates that structural fatigue and foundation failure can be influenced by dynamic ice actions. Dynamic amplification can occur due to lock-in of ice-failure at structural natural frequencies; this can be especially important for narrow structures, flexible structures and structures with vertical faces. Guidance on ice failure modes and potential vulnerability to frequency lock-in is provided in the information section (A.8.2.6). Similarly, Section D.4.7 of IEC 61400-3-1 discusses dynamic loading and indicates that ice mobility, floe sizes, ice type, ice concentration and misalignment between ice drift and wind direction can all influence the dynamic loading behaviour. The effect of any dynamic ice actions and amplification on fatigue, foundation response, and peak loads should be considered.

ICE LOAD MODELS

Ice load models are needed to create load time traces for assessing wind turbine structures designed for offshore regions with ice. The models are generally coupled to dynamic models of the turbines and support structures, so that support structure motions due to ice and other loads are fed back to the load model to properly determine the relative position of the ice feature and structure face, and potentially the relative velocities at the ice structure interface. If the structure does not move significantly, it may be sufficient to provide ice load time traces as inputs without coupling.

The inputs to the ice load model will depend on the type of feature being modelled and the design load case being considered. For fatigue, the full range of ice conditions will be modelled (or a representative subset with weightings based on their frequency). For ultimate design load cases, a single case (such as a 50-year level ice thickness) may be modelled, or a range of cases may need to be modelled (for example, a 50-year level ice thickness with different directions relative to the wind and velocities).

Types of loading events that may be relevant include first-year level ice and ridge interactions with vertically-faced fixed structures, first-year level ice and ridge interactions with sloped-faced fixed structures (typically cones), impacts from pack ice and smaller floes that do not involve crushing, and impacts from large features such as icebergs and multi-year floes.

The loads on a structure will be less than the force required to fail the ice at the structure face (i.e., the 'limit stress') if there is insufficient driving force ('limit force') acting on the interacting ice feature and its initial kinetic energy is used up in crushing. The limit force typically ramps up initially as the interacting feature decelerates; this force can take time to develop. 'Limit energy' refers to the kinetic energy of the interacting ice feature; this energy will go into ice failure and movement of the structure at a rate depending on the difference between the limit stress and limit force.

A good description of failure modes for level ice interactions with fixed narrow structures is given in Hendrikse and Nord (2019). For flexible structures, as the ice velocity increases, the load may transition from creep, intermittent crushing, frequency lock-in, and finally to crushing. The timing and occurrence of the different phases will depend on the structural mass and stiffness, as well as other parameters such as contact width, ice thickness and ice temperature. Creep occurs at very slow interaction rates, with moderate pressure applied fairly uniformly over the whole contact zone. For crushing, the pressure occurs over localized high-pressure zone areas covering around 10 percent of the contact area. For intermittent crushing, the load and structural displacement time traces follow sawtooth-like patterns, with the frequency of the pattern increasing with velocity. The load amplitude depends on the global load and structure stiffness. The contact areas are observed to increase as the load ramps up. The peak loads could reach three to four times higher than those during continuous crushing (Hornes et al., 2024). Frequency lock-in occurs when one of the structural natural modes of vibration is excited, and has been observed for frequencies from 0 Hz to 10 Hz. During the continuous crushing mode, structural oscillations are much smaller than those for frequency lock-in and intermittent crushing. Hammer et al. (2023) and Hammer (2024) demonstrate in model-scale experiments that multi-modal interactions can occur, including continuous crushing, intermittent crushing and frequency lock-in, and that ice models should be able to simulate such cases.

For very stiff structures, as the ice velocity increases, the transition is directly from creep to crushing failure, with the global maximum load highest around the transition speed (around 0.01 to 0.03 m/s). The pressures in these zones can be very high, but the average force is less than that at transition speeds.

While average global crushing pressures are fairly independent of the structure width, the peak pressures reduce as the width increases due to probabilistic averaging. This results because, during continuous crushing, the loads are transmitted through localized high-pressure zones with a fairly random distribution of pressure, so the greater the contact area, the more the associated localized forces are averaged out (e.g., Jordaan et al., 2006). Due to scale effects, crushing pressures also reduce with ice thickness.

Karna (2006) provides a spectral model for continuous crushing forces based on observed forces on the Norströmsgrund lighthouse. The random crushing force is independent of the structure's movement, and the pressure decreases slightly with ice thickness. Määttänen (1998) provided one of the earliest models for ice-induced vibration based on an empirical relationship between ice pressure and the relative velocity between the structure and ice.

Hendrikse (2017) and Hendrikse et al. (2018) describe a more recent model for simulating creep, intermittent crushing, frequency lock-in and uniform crushing of level ice against flexible structures. The model determines the ice loads as the sum of loads from individual independent elements, where each element consists of a non-linear dashpot for creep behaviour in series with a Kelvin-Voigt element (or spring and dashpot in parallel) representing the visco-elastic behaviour of the ice, and a spring element representing the elastic behaviour of the ice. The model does not explicitly account for larger failure models such as spalling and radial cracking. By modelling the independent elements (which could be considered analogous to high-pressure zones), the model can capture creep behaviour at slow velocities, the increasing contact area during intermittent crushing, and frequency lock-in associated with the ramp-up of force before failure. The model can be applied to interactions with single and multiple-degree-of-freedom structures. The code for the model has been made publicly available by the authors.

Sloped structures, such as cones, can reduce horizontal forces significantly by breaking the ice in flexure rather than crushing. The loads will depend on the slope of the cone, the width of the structure relative to the ice thickness, the flexural strength of the ice, the amount of ice that accumulates on the slope and the effect of the vertical structure at the top of the cone, if ice reaches that height. Accumulation of ice on the cone during interactions will increase in-plane compressive forces at the point of flexure, effectively increasing the flexural strength. Conical structures can shed more ice to the sides, reducing the amount of accumulated ice. Load increases can be significant if the effectiveness of flexural breaking of the ice is reduced because of too much ice accumulation or if the crushed and broken ice bonds during periods between ice movements. It is useful to note that experience in the design and subsequent load monitoring of conical protection structures on piers for the Confederation Bridge shows that ridges don't result in large loads in temperate waters and level ice up to about 0.5 m. For this particular structure design, the edge of the upward-breaking cone also helps to break up the keel of the ridge before large forces can be mobilized.

Several models are available for level ice interactions with sloped structures. Ralston (1977, 1980, IEC 61400-3:2009, ISO 19906) provides a model for level ice loads on conical structures, and Croasdale (1994, ISO 19906:2019) provides a model for level ice interactions with sloped structures, that can be adapted for application to cones..

AVAILABLE SOFTWARE

Several open-source and commercial models are available for modelling offshore wind turbines and ice loads, including the following three examples. OpenFAST is an open-source package provided by the U.S. National Renewable Energy Laboratory (NREL) with executables, source code and examples for fixed and floating offshore turbines. DNV provides the commercial packages, Bladed and Sesam, that can be used for analyzing and optimizing offshore wind turbines. HawC2 (Rinker et al., 2020) is another commercial package that has been used for modelling floating wind turbines and ice-induced vibration (Willems and Hendrikse, 2019).

Much of the recent focus on ice loads is for fixed turbines in the Baltic Sea. The model VANILLA was developed at TU Delft by Hayo Hendrikse and colleagues for simulating ice-induced vibrations and nonlinear ice loads (Willems and Hendrikse, 2019; Hendrikse and Nord, 2019) and has been coupled with Hawc2 (van der Stap et al., 2023) and BHawC (Willems and Hendrikse, 2019).

Several ice load programs have been developed for use with models for offshore turbines. DNV developed the package IceFloe (McCoy et al., 2014) under support from the US Department of Energy. While the package was developed primarily for use with OpenFAST, a DLL was created for interfacing with HawC2. Load time series can be output in Bladed format, although the models are not coupled. The University of Michigan developed the package IceDyn (Yu, 2014; Karr and Yu, 2015) under support from the U.S. Department of Energy and in cooperation with NREL. The routines are written in Fortran and coupled with OpenFAST.

The two ice load packages (IceDyn and IceFloe) included with OpenFAST together include models covering a range of ice loading scenarios. The IceDyn package includes ice load models for creep, floe splitting, non-simultaneous ice failure, individual floe impacts, random crushing, and two models for ice interactions with sloped structures. The IceFloe package includes Karna's stochastic crushing model, intermittent and lock-in crushing models referenced in the ISO and IEC standards, the model for ice-induced vibration by Määttänen , and flexural failure models by Croasdale and Ralston. All of the IceDyn and IceFloe models are coupled to the structural model in OpenFAST, i.e., the relative locations of the ice feature and wind turbine support structure are updated continuously. The Määttänen model in IceFloe also considers the updated relative velocity of the floe, i.e., how fast it is crushing into the structure face. Source code is available for all of the models. The models have not been updated by NREL since their implementation.

EXAMPLE APPLICATIONS

Hendrikse and Nord (2019) compare the failure modes and loads predicted by the Hendrikse model to the observed response of the Norströmsgrund lighthouse to a floe impact. The objective was to calibrate the model and work towards quantifying the influence of floe size and velocity on the development of sustained vibrations and hence fatigue.

The Hendrikse model was applied for a monopile structure in southern Baltic conditions (Hammer et al., 2023). The authors determined a 50-year ice thickness of 0.4 m. They then calibrated the model based on the ISO 19906:2019, Equation A.8-21, for design ice strength given as a function of return period, structure width, ice thickness and exposure to interaction events. Additional information on determining the C_R coefficient for Equation A.8-21 can be found in Hendrikse and Owen (2023). It was concluded that 'intermittent crushing and the multi-modal interaction regime give rise to the largest bending moments'.

A recent evaluation of the feasibility of using monopile wind turbines at different locations in the Baltic Sea (van der Stap et al., 2023) is relevant when considering the use of monopiles in the Great Lakes and Gulf of St. Lawrence. Monopiles were considered, due to their relatively low Levelized Cost of Energy. Van der Stap et al. (2023) created a feasibility map across the entire Baltic regarding the use of monopiles, based on potential ice-induced vibrations and high ridge loads. The ice season and level ice thicknesses across the region were estimated from temperature data, with validation checks based on measured data. Ridges were assigned consolidated thicknesses 1.5 times that of the surrounding ice, and total thicknesses equal to 12.5 times the square root of the thickness of the surrounding ice. The level ice, consolidated layer, and keel strength model inputs applied for the design load cases were based on methods from ISO 19906:2019. The unconsolidated keel friction angle and cohesion were based on values in Heinonen (2004). The ice velocity was set to 2% of the wind velocity, ignoring any potential overall effect of the wind farm on ice drift.

The required monopile mass for each location was determined based on wind and waves with no ice (using Hawc2) and with ice considered (using Hawc2 and VANILLA). The program MORPHEUS (Nielsen et al., 2022) was used to determine the required foundation design and additional monopile weight to compensate for ice loads. The main factor necessitating added steel weight was increased fatigue due to ice loading. As an approximation, based on the ice thickness map in Figure 1 and the feasibility map in Fig. 7 of van der Stap et al. (2023), monopiles are feasible if the 50-year ice thickness is less than 0.4 m, infeasible if the ice thickness exceeds 0.6 m, and potentially unfeasible for ice thicknesses in between.

A similar approach might apply to wind farms in the Gulf of St. Lawrence and the Great Lakes, where crushing from first-year level ice is the dominant form of ice loading. Fuglem et al. (2024) provide an initial estimate of exposure to level ice crushing across the Gulf of St. Lawrence based on sea ice charts. The sea ice charts tend to be conservative, as it is used to inform shipping of possible risks, and should be further assessed. Differences in the conditions between the Baltic Sea and the Gulf would need consideration. The Gulf of St. Lawrence is smaller than the Baltic Sea and further south, but it is open to the Atlantic Ocean and has less warming influence from the Gulf Stream. If the Gulf of St. Lawrence sees greater movement of ice due to winds than in the Baltic, ice thicknesses based on freezing-degree days might not be sufficiently accurate.

Croasdale and Allyn (2018) modelled level ice and ridge ice loads on monopile wind turbine structures with upward and downward-sloping cones. Croasdale et al. (2019) apply the model to develop stochastic ice load time series for input to demonstrate that the structure satisfies design load case checks.

A preliminary review of sea ice loads (Thijssen et al., 2022) and iceberg loads (Stuckey et al. 2022, Fuglem et al. 2022) on a variety of floating wind turbine designs proposed to provide power to oil platforms on the Grand Banks showed that wind power may be feasible considering the frequency and severity of events for a 50-year design window, and given that iceberg management is already provided for the oil platforms. The model for pack-ice loads is based in part on observed loads on the moored offshore conical drilling platform Kulluk during Arctic operations (Wright, 1999). The emphasis was on mooring loads rather than impact dynamics. For conditions with smaller ice floes and non-pressured ice (common in marginal ice regions), the loads depend on the width of the floating platform but may be tolerable. Loads due to impacts by smaller icebergs depend on the floating-platform type, but could also be tolerable. The floating platforms were treated as rigid, and further analysis of the structural dynamics on impact is required.

EXAMPLE CALCULATION USING OPENFAST MODEL

In this section, we evaluate OpenFAST's model for isolated floe interactions (IceDyn Model 6), considering the IEA 15 NW reference wind turbine (Gaertner et al. 2020). Derradji-Aouat et al. (2025) recently investigated the IceFloe crushing model for the same structure when operating in production mode.

The IceDyn manual provides two examples. The first is where there is a large driving force acting on the floe, and the load ramps up to the driving force and stays at that level. In the second example, the load ramps up until the ice floe splitting force limit is reached, at which time the load goes to zero. The floe impact model is coupled with the OpenFAST structure model so that the relative position of the ice floe and monopile is correctly determined, but, as will be noted, issues result because the crushed ice is not removed.

An initial analysis was done for a 100 m x 100 m floe, 1.5 m thick, with a crushing strength of 0.5 MPa, moving at 0.5 m/s and timed to impact at 120 s from the start of the simulation. The water depth is 45 m. The wind speed is set to zero so that the response of the turbine can be more clearly assessed. When the model was run with zero wind load, there was an increase in the initial structural vibrations relative to the initial response when a wind load was applied. The initial monopile angle and tower top position were adjusted to reduce this initial response. The model outputs are shown in Figure 2. The red line at 100 s signifies the start-up time typically considered to eliminate transients when conducting 10-minute simulations for design load cases; only values after 100 s are referenced. For the demonstrations here, only 200 s were required to show the effects of the floe impact. The positive x-direction is in the direction of the initial ice floe movement, the y-direction is at 90 degrees to this in the horizontal plane.

Following impact (Figure 2A and B), the floe is reflected off the monopile at 0.5 m/s (i.e., no energy is lost in crushing). On further investigation, it was determined that the model does not account for the removal of crushed ice and that the impact force continues after contact should have been lost. This means that the impulse load transfer during impacts is much larger than it should be. In a follow-up analysis (not presented), a small driving force was applied to the back of the impacting floe. The peak load is higher, as expected, though the floe is still reflected off the monopile, and now the driving force acts to bring the floe back, resulting in repeated impacts with the same load magnitude. These limitations should be noted when using the model. For example, one could try to match the correct impulse for the actual floe impact considered. To model other shapes and remove crushed ice, it will be necessary to implement updated code coupled with the OpenFAST code for the structure response.

The effect of the impact is apparent in all of the structural responses shown (Figure 2C to N). The nacelle acceleration in the x-direction (Figure 2C) following impact is around 0.6 $m/s^{2,}$

and the acceleration in the y-direction is much smaller. This is in contrast to the case with a 15 m/s wind, where the wind induces higher (resonant frequency) accelerations in the y-direction than in the x-direction (Figure 2). The shear at the mudline (Figure 2E) ranges from -1.5 MN to 4 MN while the shear at the tower base (Figure 2G) ranges from -0.5 MN to 0.5 MN. The surge at the waterline went from 0.03 m to -0.07 m (a 0.1 m range) while the displacement at the tower top went from -0.22 m to -0.86 m (a 0.64 m range). The hydrodynamic loading on the monopile ranged from -1 MN to 1 MN. This loading is due to an added mass effect as the monopile is being accelerated through the water in the x-direction. The floe impact resulted in displacements of the blade tip in the x-direction from -0.4 m to 0.5 m.

In the second example, a 15 m/s wind is included (Figure 3). Most of the responses due to the floe impact are either dampened out or overwhelmed by responses to the wind. The only clearly seen responses are the shear and moment at the mudline (Figure 3C and D). Note that the nacelle acceleration in the y-direction is much larger (-0.9 m/s^2 to 1.0 m/s^2) than in the x-direction (-0.4 m/s^2 to 0.4 m/s^2). This results because damping in the x-direction due to the mean wind force does not occur in the y-direction, which vibrates at one of the system's natural frequencies. Most often, the directions of the wind and ice loading will be different, but the effect of the aerodynamic damping in different directions still needs consideration (Hammer and Hendrikse, 2023).

CONCLUSIONS

To date, there is limited experience with bottom-fixed offshore wind turbines in regions with sea ice and no experience with floating systems in sea ice. Most of the work on ice loads on bottom-fixed offshore wind turbines has been carried out for the Baltic and Bohai Seas. In the Baltic, concrete structures with cones have been installed in very shallow water, and monopile and jacket structures have been implemented in deeper water, but where sea ice is relatively infrequent and thin. A recent study indicates that monopiles would presently be viable for 50-year ice thicknesses up to approximately 0.5 m.

No offshore wind turbines have been installed in Canada. The ice in the Great Lakes is relatively thin, such that monopiles could potentially be used, though the higher strength of freshwater ice needs consideration (note that the northern Baltic is brackish). Studies have been carried out on monopiles with conical protection structures for the U.S. Great Lakes, but these have not been implemented to date.

Ice conditions in the Gulf of St. Lawrence are varied and become more severe as one moves north. More robust designs or new innovative designs may be required (with economic viability demonstrated) before wind developments proceed. Much of the gulf is in deeper water and would require the use of floaters.

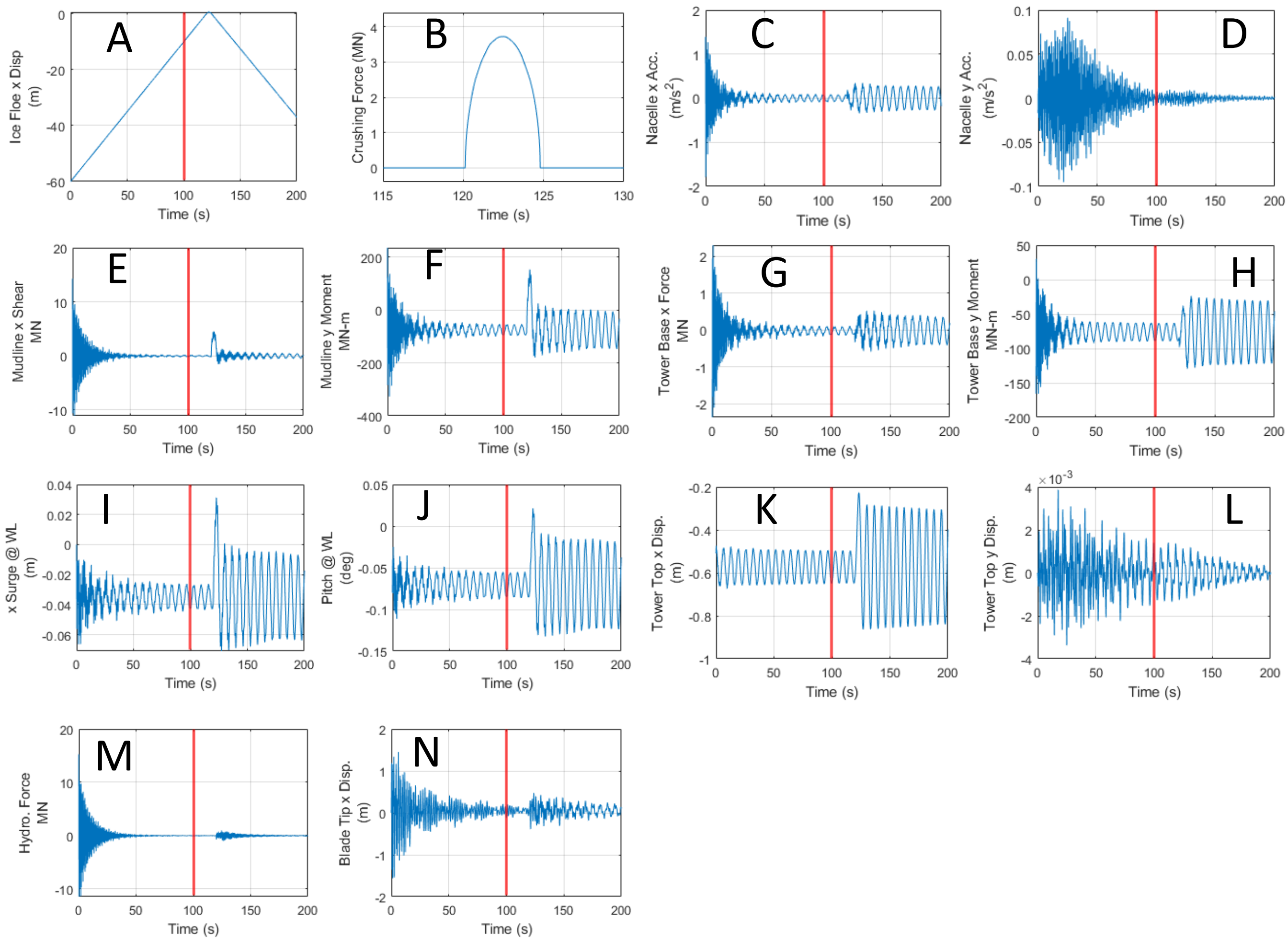

Figure 2. Responses for Case 1 with zero wind applied to better highlight the response to the ice floe impact (The period 0 to 100 s, i.e. the red line, is considered transient and discounted. The impact was timed to occur at 120 s)

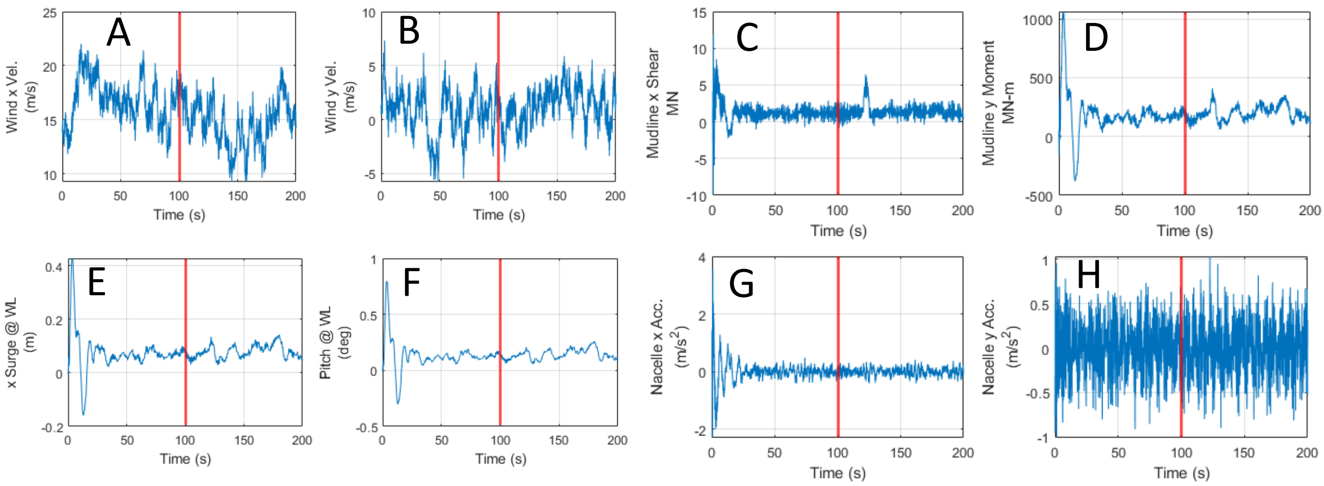

Figure 3. Responses for Case 2 for production mode with a 15 m/s mean wind speed (The period 0 to 100 s, i.e. the red line, is considered transient and discounted. The impact was timed to occur at 120 s)

The Grand Banks sees marginal pack ice and infrequent iceberg incursions. Wind energy developments could be viable if interaction events are infrequent and design load case criteria are met. In the northeastern banks, the water depth ranges from 80 m upwards, and icebergs are a concern in addition to occasional incursions of sea ice. Some initial evaluations of floating systems for supplying energy to oil production platforms have been carried out, though further evaluation of the effect of impact dynamics is required. The southern banks see significantly reduced frequencies of both sea ice and icebergs. Much of the region that could be developed for wind energy is at depths of 60 to 80 m, which might require jacket structures or extended monopiles supported with guy wires. The possibility of extreme but rare events that could damage multiple turbines and disrupt the power supply may need consideration (i.e. heavier northern ice being blown further south), in which case, more stringent design load cases associated with longer return periods would need consideration.

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.

The OpenFAST software includes packages for modelling ice loads. The models have not been updated recently, nor applied extensively, and have limitations. As shown here, the model for individual floe impacts does not account for the removal of crushed ice, with the effect that fictitious forces act on the floe and structure after the impact should have ended. In terms of modelling ice-induced vibrations, newer models, such as those implemented within VANILLA and which determine whether continuous crushing, intermittent crushing or frequency lock-in will occur, should be given consideration. New models considered for use within OpenFAST will need to be programmed for appropriate coupling.

REFERENCES

Croasdale, K. and Allyn, N., 2018, Ridge Loads on Wind Turbine Structures, OTC-29107

Croasdale, K., Thijssen, J. and Allyn, N., 2019, Ice load signatures for ridge actions on wind turbines with conical collars, POAC

Croasdale, K.R. and Cammaert, A.B., 1994. An Improved Method for the Calculation of Ice Loads on Sloping Structures, Hydrotechnical Construction, Vol. 28, No. 3, March.

D'Agostino, J., 2025, Feasibility study reveals little benefit in lake turbines, Observer, May 08, 2025, https://www.observertoday.com/news/top-stories/2023/01/feasibility-study-reveals-little-benefit-in-lake-turbines/

Derradji-aouat, A., Stuckey, P., Fuglem, M., Turnbull, I., 2025, Effects of Ice, Wind, Waves and Currents on Offshore Wind Turbines Destined for Atlantic Canada, OMAE

DNV, 2021, DNVGL-ST-0437 Load and site conditions for wind turbines

Environment and Climate Change Canada, 2022. Factors influencing Great Lakes ice extent and thickness.

Fuglem, M., Shayanfar, H., Liu, L., T. King, and Paulin, M., 2022, Evaluation of five floating wind turbine platform designs with respect to 50-year return period iceberg impact, 26th IAHR International Symposium on Ice, 19-23 June, Montreal, Canada.

Fuglem, M., Stuckey, P., Derradji-Aouat, A., McKenna, R. and Ralph, F., 2024. Development of Offshore Wind in Atlantic Canada: Regulations, Standards and Technical Challenges, Oceans 2024.

Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., & Viselli, A. (2020). Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report (tech. rep.). https://www.nrel.gov/docs/fy20osti/75698.pdf

Hammer, T. C. (2024). Ice-induced vibrations of offshore wind turbines: An exploration of scaling, hybrid testing, and numerical simulations [Delft University of Technology]. In TU Delft University. https://doi.org/10.4233/uuid:b3b5eb45-1581-44b6-975b-05a7ac74de8e

Hammer, T. C., & Hendrikse, H. (2023). Experimental study into the effect of wind-ice misalignment on the development of ice-induced vibrations of offshore wind turbines. Engineering Structures, 286, 1–17. https://doi.org/10.1016/j.engstruct.2023.116106

Hammer, T. C., Willems, T., & Hendrikse, H. (2023). Dynamic ice loads for offshore wind support structure design. Marine Structures, 87, 1–19. https://doi.org/10.1016/j.marstruc.2022.103335

Hammer, T., Willems, T. & Hendrikse, H., 2023, Dynamic ice loads for offshore wind support structure design, Marine Structures

Heinonen, J., 2004, Constitutive modelling of ice rubble in first-year ridge keel. Master's thesis, Helsinki University of Technology.

Hendrikse H, Ziemer G, Owen C., 2018, Experimental validation of a model for prediction of dynamic ice-structure interaction. Cold Regions Science and Technology

Hendrikse, H., & Nord, T., 2019, Dynamic response of an offshore structure interacting with an ice floe failing in crushing, Marine Structures

Hendrikse, H., & Owen, C. C., 2023, Application of the suggested ice strength coefficients in ISO 19906 to intermittent crushing. In Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions (Proceedings - International Conference on Port and Ocean Engineering under Arctic Conditions). POAC.

Hendrikse, H., 2017. Ice-induced vibrations of vertically sided offshore structures. PhD thesis. Delft University of Technology.

Hendrikse, H., 2024, Ice engineering challenges for offshore wind development in the Baltic Sea, 27th IAHR International Symposium on Ice, Gdańsk, Poland.

Hornnes, V., Hendrikse, H., & Høyland, K. V. (2024). Establishing the ice strength coefficient from mean crushing loads and a theoretical velocity effect. Proceedings of the 27th IAHR International Symposium on Ice.

IEA 15 NW reference wind turbine (Gaertner et al. 2020)

IEC 61400-1:2019 Wind energy generation systems - Part 1: Design requirements

IEC 61400-3-1:2019 Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines

ISO 19904-1:2019 Petroleum and natural gas industries — Floating offshore structures Part 1: Ship-shaped, semi-submersible, spar and shallow-draught cylindrical structures Published (Edition 2, 2019)

ISO 19906:2019 Petroleum and natural gas industries — Arctic offshore structures

ISO 35104:2018 Petroleum and natural gas industries — Arctic operations — Ice management

Jordaan, I., Frederking, J. and Li, C., 2006, Mechanics of Ice Compressive Failure, Probabilistic Averaging and Design Load Estimation, IAHR.

Karna, T. et al., A Spectral Model for Forces due to Ice Crushing, Journal of Offshore Mechanics and Arctic Engineering, May 2006.

Karr, D., Yu, B., 2015 Draft: FAST Ice Module Manual, University of Michigan, April 2015

King, T., Ralph, F., Fuglem, M., Stuckey, P., Thijssen, J., Turnbull, I., Huang, Y., Talimi, V., Liu, L., Yulmetov, R., Shayanfar, H., Howell M. and Paulin, M., 2022, Ice Risk Analysis for Floating Wind Turbines, Offshore Newfoundland and Labrador. OTC

King, T., Stuckey, P., and Fuglem, M., 2025, Power Generating Potential on the Grand Banks Using Fixed-Bottom Wind Turbines, POAC2025

Korzhavin, K.N., Action of Ice on Engineering Structures, US Army CRREL Translation TL260, Hanover, N.H., USA, 1971.

Määttänen, M., Numerical Model for Ice Induced vibration load lock-in and Synchronization, Proceedings of the 14th International Symposium on Ice, Potsdam, NY, USA, 1998, Vol. 2, pp 923-930.

McCoy, T.; Brown, T.; Byrne, A., 2014, Ice Load Project Final Technical Report – Creation of a Model for Interaction of Bottom-Fixed Wind Turbines with Surface Ice for use with Common Simulation Codes, DNV-GL Report DDRP0133 for U.S. Department of Energy

Nielsen. M., Hindhede, D., Palmer, M., Thilsted, C., 2022, A highly efficient and rapid cost-optimization framework for offshore wind turbine foundations for an entire windfarm site - IOWTC2022

NYSERDA, 2022, New York Great Lakes Wind Energy Feasibility Study, New York State Energy Research and Development Authority (NYSERDA) Report Number 22-12. Prepared by the National Renewable Energy Laboratory, Advisian Worley Group, and Brattle Group/Pterra Consulting. nyserda.ny.gov/publications

Pollack, N., 2023, Only Permitted Great Lakes Offshore Wind Farm Put on Hold, Inside Climate News, https://insideclimatenews.org/news/08122023/icebreaker-offshore-wind-halted-ohio/?utm_source=chatgpt.com

Ralston, T., 1977, Ice Force Design Considerations for Conical Offshore Structures, POAC Conference.

Rinker, J., Gaertner, E., Zahle, F., Skrzypiński, W., Abbas, N., Bredmose, H., ... & Dykes, K. (2020). Comparison of loads from HAWC2 and OpenFAST for the IEA Wind 15 MW Reference Wind Turbine. In Journal of Physics: Conference Series (Vol. 1618, No. 5, p. 052052). IOP Publishing.

Stuckey, P., Y. Huang, T. King, and Paulin, M., 2022, Regional Assessment of Iceberg Actions on Five Floating Offshore Wind Turbine Platforms, 26th IAHR International Symposium on Ice. 19-23 June, Montreal, Canada.

Thijssen, J., Fuglem, M., King, T., Paulin, M., 2022, Evaluation of Floating Wind Turbine Platform Designs for Sea Ice Loads, IAHR

Van der Stap, F. L., Nielsen, M. B., Owen, C. C., van der Male, P., & Hendrikse, H., 2023, On the feasibility of monopile foundations for offshore wind in the Baltic Sea. In Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions

Willems, T., & Hendrikse, H. (2019). Coupled Simulation of Ice-Structure Interaction of Offshore Wind Turbines in Bhawc Using Vanilla. In POAC 2019 - 25th International Conference on Port and Ocean Engineering under Arctic Conditions: June 9-13, 2019, Delft, The Netherlands (Vol. 2019-June)

Wright, B., 1999, Evaluation of Full Scale Data for Moored Vessel Stationkeeping in Pack Ice PERD/CHC Report 26-200.

Yu, B., 2014, Offshore Wind Turbine Interaction with Floating Freshwater Ice on the Great Lakes, PhD Thesis, Naval Architecture and Marine Engineering, The University of Michigan