POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

Analysis of ice-induced vibration of a 15MW offshore monopile wind turbine under vertical continuous brittle crushing and conical bending crushing

Shaowei Tang [1], Yan Qu [1*], Haoyang Yin [1], Haian Zhang [1]
(1. School of Marine Science and Engineering, South China University of Technology, Guangzhou, China
* Correspondence: quyan@scut.edu.cn)

ABSTRACT

Ice-induced structural vibrations are becoming increasingly important as offshore wind power expands into colder regions. In this study, the ice-induced vibration response of a 15 MW monopile offshore wind turbine is comparatively analysed, focusing on the effect of the ice-breaking cone (IBC). The structural response is investigated for two cases: continuous brittle crushing (CBR) without IBC and bending crushing with IBC. Results show that while IBC reduce peak ice loads by causing ice to fail in bending, their impact on reducing structural vibration is limited. The response under ice loading is similar for both configurations (with and without IBC). These findings suggest that for large-capacity monopile offshore wind turbines, the use of IBCs may not result in significant vibration damping and that IBC can be omitted to optimise cost and structural performance.

KEY WORDS: Ice-induced vibrations; Monopile foundation; Offshore wind turbine; Ice-breaking cones.

1. INTRODUCTION

With increasing global attention to climate change, offshore wind power has rapidly developed over the past decade, expanding into regions traditionally considered harsh environments, such as areas with sea ice. Compared to onshore wind turbines, offshore wind turbines (OWTs) face more complex environmental challenges, including the continuous effects of wind, ice, earthquakes, and waves, which can cause significant dynamic responses in structures and have become a research hotspot in recent years (Zhang and Wang, 2022).

Practical engineering applications have shown that sea ice poses a significant threat to the operation and safety of offshore structures. In fact, the interaction between sea ice and offshore structures is a complex dynamic process. During an interaction between an offshore structure and a drifting level ice, various failure modes of ice could take place: bending, buckling, cracking/splitting or crushing. These failure modes depend on the shape of the structure at the water level. The sloping shapes cause the level ice to fail by bending, whereas the vertical shapes cause the level ice to fail by crushing. The ice loads due to crushing are higher than those due to other failure modes (Sanderson, 1988), and ice crushing may induce severe steady-state vibrations as well. Therefore, ice crushing can be regarded as the most important failure for the support structure design of OWTs. There exist various international standards that provide guidance for the design of offshore structures in arctic and cold regions. According to the classification in ISO 19906 (2019), the ice crushing mode can be divided into three categories, namely intermittent ice crushing at a low ice velocity, frequency lock-in crushing at a moderate ice velocity, and continuous brittle crushing at a high velocity.

Many studies have investigated ice loading and ice-induced vibrations of offshore vertical structures under crushing failure. Bekker et al. (2009) carried out simulations of the ice-structure interaction between the ice cover and the offshore structures. Kuutti et al. (2013) simulated ice crushing against a rigid vertical structure using the cohesive element method. Hendrikse and Nord (2019) proposed a model to simulate the dynamic interaction between a drifting ice floe and a vertically sided offshore structure. The effect of ice floe size and ice drift on the interaction between ice and structure was studied. Berg et al. (2022) conducted basin tests with a vertical sided cylindrical pile loaded by ice that fails in the crushing mode. Intermittent crushing, frequency lock-in and continuous brittle crushing were observed in the tests. Hammer and Hendrikse (2024) investigated the use of a Hardware-in-the-Loop (HiL) technique applied in model ice experiments to enable the analysis of offshore structures with low natural frequencies under dynamic ice loading.

Some researchers have focused on the interaction between sea ice and OWTs. Wang et al. (2016) analyzed the impact of ice-induced vibrations (IIVs) on OWTs in the Bohai region using numerical methods and found that the acceleration response at the top of the OWTs is significantly caused by IIVs. Based on the Matlock and Määttänen models, Ye et al. (2019) simulated IIVs on OWTs and found that IIVs have a significant impact on OWTs, especially on the tower. Song et al. (2019) simulated the interaction between level ice and wind turbine tower using the finite element method (FEM). Ji and Yang (2022) developed a coupled DEM-FEM method to simulate the interaction be tween the sea ice and the monopile structure of OWT. Hammer et al. (2022) conducted an experimental study at Aalto Ice Tank to investigate ice-induced vibrations of an offshore wind turbine on a monopile foundation. Wang et al. (2023) analysed the ice-induced vibration of fixed- bottom wind turbine towers and underscores the importance of robust ice-load integration in design strategies for offshore wind turbines, especially in regions susceptible to ice.

The frequency lock-in (FLI) is one of particular interest. It is critical aspect of ice-induced vibrations which develop due to the synchronization between the structure and ice. Huang et al. (2013) simulated the interaction between sea ice and structures through model tests and found that vertical pile structures can exhibit steady-state vibrations under ice loads, which are determined by the interaction between ice and the structure. If such steady-state vibrations occur in flexible systems like offshore wind turbine foundations, they can cause significant dynamic responses, affecting the normal power generation of the upper units and even threatening the safety of the entire structural system. Hendrikse et al. (2017) studied the interaction between ice and vertical offshore wind turbines when frequency lock-in occurs, resulting in high amplitude oscillation of the structure. Seidel and Hendrikse (2018) studied sea ice-induced frequency lock-in for offshore wind turbine monopole and an analytical method is presented to assess FLI of monopile support structures for offshore wind turbines, subjected to loading by floating sea ice. Yin et al. (2023) analysed the ice-induced FLI vibration of bottom fixed wind turbine structure. The analysis showed that the magnitude of the FLI vibration is larger than the vibration caused by continuous brittle ice crushing.

Bending crushing dominates when sea ice interacts with conical structures. To mitigate ice-induced vibrations, conical structures have been suggested for most offshore structures where ice is present because they can induce bending failure in level ice by introducing a vertical force component into the total interaction force using upward or downward cones (Xu et al., 2014). The cone reduces the ice load magnitude and ice-induced structural response compared to a cylindrical structure with the same waterline diameter (Barker et al., 2014). Jussila and Heinonen (2012) studied the ice-substructure interactions of conical and cylindrical monopile, and various configurations are studied by changing the cone angle and the foundation depth. According to the results, the vibration amplitude of the conical substructure is significantly reduced compared to the cylindrical shell. Wang et al. (2022) used a finite element analysis method to analyze the vibration response and fatigue of offshore wind turbines foundations before and after the installation of the IBCs under the same extreme ice conditions. The results show that the vibration response of the conical structure is greatly reduced, which makes the offshore wind turbine infrastructure have greater resistance to the dynamic ice loads. Zou and Bricker (2024) utilized a coupled cohesive element method-finite element method to simulate the behavior of ice sheets and ice-structure-soil interaction. The impact of conical structure on offshore wind turbine stability is evaluated, demonstrating a notable reduction in ice forces.

Monopile foundations are the preferred foundation type for offshore wind power development in ice-covered areas due to their simple design and installation, which typically achieve the lowest levelized cost of energy (van der Stap et al., 2023). Currently, offshore wind turbines in ice-covered areas often add ice-breaking cones to monopile structures to transform the ice load failure mode into bending failure, thereby reducing the ice loads acting on the monopile foundations. However, during ice-free periods, the presence of ice cones increases the waterline area of the foundation, significantly increasing wave loads and posing a threat to the safety of offshore wind turbines (Tang et al., 2021; Zhu et al., 2021). With the application of large-capacity OWTs, the diameter of the tower continues to increase, and so does the diameter of the IBCs. Therefore, it is necessary to carefully study the interaction between sea ice and conical OWTs and assess their applicability to ensure the safe operation of offshore wind power in ice-covered areas.

There is no intuitive conclusion in the ISO and IEC standards on whether offshore wind turbines should be fitted with ice-breaking cones. In order to make a reasonable judgment, it is necessary to compare the ice load and ice-induced vibration and evaluate their applicability. This study presents a comparative analysis of ice-induced vibration responses in a 15 MW monopile offshore wind turbine, with a particular focus on the influence of IBCs. The ice load models and important parameters of the wind turbine model used in the analysis are introduced. The structural response of a monopile wind turbine structure under continuous brittle crushing is analysed and compared with a wind turbine structure with an IBCs. Finally, the structural responses of the two models under combined wind-ice loads are analyzed and compared. It is suggested that for large-capacity monopile offshore wind turbines, the use of IBCs may not offer significant vibration mitigation benefits and could be omitted to optimize cost and structural performance.

2. WIND TURBINE MODEL

2.1 Wind Turbine Model Parameters

IEA 15MW RWT is a three-blade 15MW wind turbine developed by the International Energy Agency (International Energy Agency, IEA). The basic parameters of the wind turbine are shown in Table 1. The wind turbine finite element model reference IEA 15MW wind turbine is modeled in SIMA software, which consists of the main components such as foundation, tower, nacelle and rotor with blade. The rotor radius is 120 m, the hub height is 150 m, and the water depth is 30 m. The bottom of the tower is 15 m above the static water surface, the bottom diameter of the tower is 10 m, and the top diameter of the tower is 6.5 m. The underwater portion of the supporting structure has a constant diameter with a diameter of 10 m. The tower was designed as an isotropic steel tube. Its material density is 7.85 e^3 kg/m3, Young's modulus is 2 e^{11} Pa and shear modulus is 7.93 e^{10} Pa. The influence of soil on the structure is not considered in the finite element model, and the seafloor boundary conditions are assumed to be fixed, simplifying the foundation in a solid-supported form.

The ice-breaking cone is arranged in the form of double cones, with a maximum diameter of 12 m, cone height of 4 m, and cone angle of about 63.5. In order to better simulate the interaction between sea ice and the cone, in the finite element model, using discrete unit section to simulate the cone angle, the unit mass and moment of inertia is modified, to match the physical characteristics of the cone attached to the support structure. No deformation in the cone is considered.

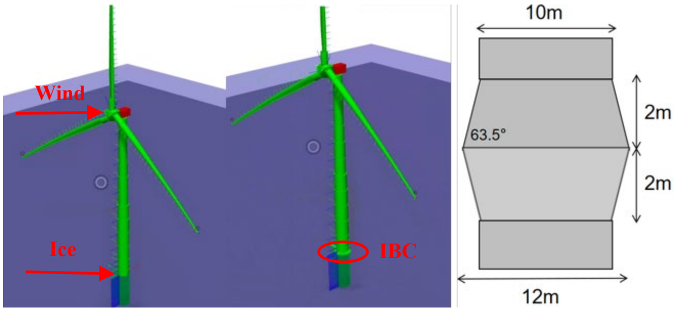

Figure 1. 15MW wind turbine model and IBC parameters

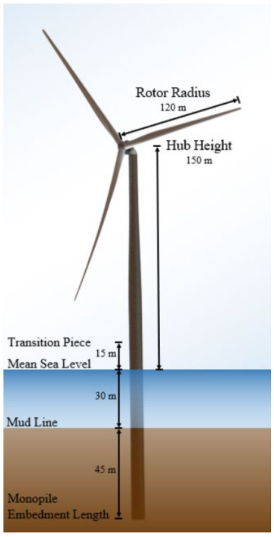

Figure 2. The IEA Wind 15-MW reference wind turbine (Gaertner et al., 2020)

Table 1. Key parameters of IEA 15MW wind turbine

Parameter	Units	Value
Cut-in wind speed	m/s	3
Rating wind speed	m/s	10.59
Cut-out wind speed	m/s	25
Blade mass	t	65
Rotor nacelle assembly mass	t	1017
Tower mass	t	860

Minimum rotor speed	rpm	5.0
Maximum rotor speed	rpm	7.56

2.2 Model Verification

The accuracy of the model plays a decisive role in ensuring the accuracy and reliability of the numerical setting, and the modal analysis of the model is a key step to verify its accuracy. The mode analysis of the wind turbine model structure is conducted to obtain the natural frequencies of the structure, and the corresponding mode characteristic frequency is shown in Table 2. Hammer et al. (2023) reproduced the interaction of an idling and operating 14 MW turbine with ice representing the conditions of a 50-year return period in the southern Baltic Sea in a study that referred to scaled modal information at the point of ice-structure interaction in the structural set-total mass model and at the top of the tower. The modal damping applied to each mode of our model was set with reference to this study and to the Elastodyn tower input file in OpenFAST.

Rayleigh damping is widely used in engineering to construct the damping matrix for solving motion equations with finite element tools (Jussila et al., 2013). The simplest way to introduce damping into the motion equation is through proportional damping matrices related to mass or stiffness. However, the commonly used version of Rayleigh damping is a combined damping matrix, divided into parts proportional to mass and stiffness. Assuming that the structure's damping matrix is a linear combination of the mass matrix and the stiffness matrix *($C=\alpha M+\beta K$)*, where α is the mass damping coefficient and β is the stiffness damping coefficient.

$$\zeta_i = \frac{C_i}{2\sqrt{M_i K_i}} = \frac{\alpha M_i + \beta K_i}{2\sqrt{M_i K_i}} = \frac{1}{2}\left(\frac{\alpha}{\omega_i} + \beta \omega_i\right) \tag{1}$$

Table 2. Natural frequencies of 15 MW OWT (Unit: Hz)

System eigenmode	Frequency(Hz)		Structural damping ratio
	CYLINDER	CONE	
1st Tower F-A	0.1472	0.1477	1.0%
1st Tower S-S	0.1474	0.1480	1.0%
2nd Tower F-A	0.9900	0.9907	1.0%
2nd Tower S-S	1.1317	1.1324	1.0%

3. ICE LOADS

3.1 Vertical Structure Ice Loads

Based on the classification in ISO 19906 (2019), the following time-varying ice interaction processes can be characterized: Intermittent crushing (ICR) takes place when a compliant structure interacts with the ice at a low speed described by a saw-tooth load pattern (Figure 3(a)). At intermediate ice velocity frequency lock-in (FLI) vibration may occur described by harmonic vibration (Figure 3(b)). At high velocity, typically > 0.1 m/s, continuous brittle crushing (CBR) takes place, in which both the ice load and the response are random (Figure

3(c)).

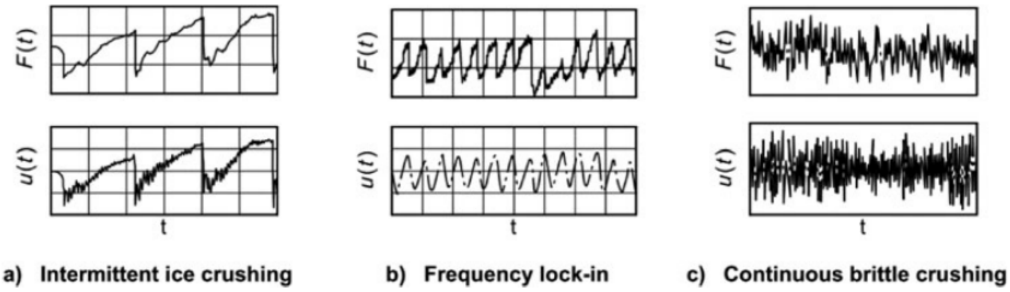

Figure 3. Time-varying interaction processes under crushing

The ice load under continuous brittle crushing is characterized as a stochastic crushing process around a roughly constant mean value. The order of load magnitude is lowest of all ice-induced vibration regimes. The load signal has no obvious periodicity, and neither does the ice-induced structural displacement. The structural displacement is typically characterized by a small-amplitude oscillation of the structure around a mean displacement. Relatively high and nearly constant relative velocity between structure and the ice occurs. During brittle crushing, the ice sheet breaks up into powder form, interspersed with a number of larger-sized fragments, the largest of which have a diameter comparable to the ice thickness. The broken ice is crushing in both upward and downward directions from the ice-structure contact surface. Several radial cracks are sometimes formed inside the ice sheet. Field test observations show that brittle crushing can occur when the rapid movement of ice interacts with the structure. The amplitude of structure vibration under brittle crushing ice force is smaller than frequency lock-in (FLI) vibration and larger than vibration under other ice forces. Brittle extrusion crushing is the most common form of ice force on vertical structures, the ice force is large, and the amplitude of structural vibration caused by it is also large, which is one of the main contents of the study of ice loading on vertical structures.

For the FLI of offshore wind turbines, sea-ice parameters can be limited by two aspects: ice speed and ice thickness. In order to address the challenges of ice-induced vibration in fixed-bottom offshore wind turbines, especially the risk of FLI, Wang et al. (2024) introduce an innovative FLI analysis method based on the ductile damage-collapse (DDC) mechanism. The ductile damage-collapse process is triggered when the ice velocity approaches the ratio of the damage length to the natural period of the structure, leading to FLI. They found that FLI occurs on the JZ20-2MSW platform in the Bohai Sea when the ice speed is 2cm/s to 4cm/s, and the ice-breaking length of the structure when FLI occurs is 1cm~2cm, and the probability of ice speed and ice thickness when f FLI occurs for a 5MW offshore stationary wind turbine is calculated according to the DDC theory, and the joint probability distribution combining the two constraints of ice thickness and ice speed indicates that the probability of the occurrence of FLI is very low, about 0.007%. Since 15MW offshore wind turbines have greater horizontal stiffness than longer vibration periods, their FLI has a lower probability of occurring. Therefore, in this paper, we do not consider the effect of FLI and will simply analyse the structural response under continuous brittle crushing.

1. Extreme ice force model for vertical structure

The static ice force of the vertical structure is calculated according to the formula given in ISO 19906 (2019) Specification for Planning, Design and Construction of Fixed Offshore Structures in Icing Environments, as follow:

$$F_G = p_G \cdot h \cdot w = C_R\left[\left(\frac{h}{h_1}\right)^n \left(\frac{w}{h}\right)^m + e^{\frac{-w}{3h}}\sqrt{1+5\frac{h}{w}}\right] \cdot h \cdot w \tag{2}$$

In the formula: p_G is the average ice pressure (MPa); w is the contact width between ice and the structure; h is the ice thickness; h_1 is the reference ice thickness, taken as 1 m; m is the empirical coefficient for contact width effect, taken as -0.16; n is the empirical coefficient for ice thickness effect, taken as $-0.5+h/5$ when the ice thickness is less than 1m; C_R is the sea ice strength coefficient (MPa), recommended to be 1.8 MPa for Bohai Bay.

2. Continuous brittle crushing dynamic ice model

Continuous brittle crushing is the most common vibration problem of vertical structures. Due to the large vibration of the ice force, the dynamic effect is one of the important characteristics of the ice force. When considering the dynamic action of the load, we usually analyze the load into two parts, that is, the load can be decomposed into the fluctuation component and the straight flow rate:

$$F(t) = F_{mean} + F_d(t) \tag{3}$$

Here, $F(t)$ is the ice force acting on the structure, F_{mean} is the average value of the ice force, and $F_d(t)$ is the fluctuation component of the ice force. The size of the fluctuation component is the most important index of the dynamic load, which directly affects the vibration response level of the structure. In the analysis of the crushing ice force, the ratio of the standard deviation of the ice force to the mean value of the ice force is the action strength of the dynamic ice force:

$$I_F = \frac{\sigma_f}{F_{mean}} \tag{4}$$

Where σ_f is the standard deviation of the ice force, and I_F is the coefficient of difference in the ice force. Based on observations, the intensity, I_F, varies between 0.2 and 0.5, with a mean value which is in the order of 0.35 to 0.4. A value of 0.4 is recommended (McCoy et al., 2014).

$$F_{max} = F_{mean} + m\sigma_f \tag{5}$$

$$\sigma_f = \frac{I_F}{1 + kI_F} F_{max} \tag{6}$$

$$F_{mean} = \frac{F_{max}}{1 + kI_F} \tag{7}$$

Here, F_{max} is the peak global ice load during continuous brittle crushing, and m usually takes 3 as the estimate of the 99.7% maximum value (Kärnä et al., 2007). The peak global ice load during continuous brittle crushing was calculated using the extreme ice force calculation formula in ISO 19906 (2019). The formula is given in equation (2)

For the pulsating component of the ice force, Kärnä et al. (2004) establishes the power spectral density function based on the measurement data of the field tests of the continuous extrusion of the sea ice in the Bohai Sea and the Baltic Sea.

$$\tilde{S}(f) = \frac{fS(f)}{\sigma_f^{\,2}} = \frac{af}{1 + k_s a^{1.5} f^2} \tag{8}$$

Where $\tilde{S}(f)$ is auto-power spectrum ; f is frequency; parameter a is related to ice speed,

$a = bv^{-0.6}$, b is empirical constant, take 1.34; k_s is empirical constant, the value is 3.24.

3.2 Conical Structure Ice Load

1.Extreme Static Ice Force Model for Conical Structures

The static ice force for conical structures is calculated according to the Ralston model in ISO 19906 (2019). The Ralston model, based on the plastic behavior of ice, is widely cited. The Ralston plastic analysis divides the horizontal ice force into H_B (crushing component) and H_R (climbing component). The total force is given by:

$$F_H = H_B + H_R \tag{9}$$

$$H_B = \frac{\sigma_f h^2}{3} \frac{tan\alpha}{1 - \mu g_r} \left[\frac{1 + Yxlnx}{x - 1} + G(x-1)(x+2) \right] \tag{10}$$

$$H_R = W \frac{tan\alpha + \mu E_2 - \mu f g_r cos\alpha}{1 - \mu g_r} \tag{11}$$

Where Y is based on the yield criteria selected for the analysis. The value provided for the Tresca criteria is: $Y = 2.711$. And G is a non-dimensional term relating the weight to the strength of the ice, W is the weight of the ice ride-up on the cone. For the specific parameters and formulas, refer to ISO 19906 (2019).

Table 3. Calculation parameters and values of cone load

Parameter	Units	Value
Cone diameter	m	12
Sea ice density	kg/m^3	910
Bending strength of sea ice	kPa	700
Cone Angle	deg	63.5
Factor of friction on the cone surface		0.1

2. Ice Force Model for Conical Structures

Based on ice force measurement data from the conical top structure pressure box in the Bohai Bay, Qu et al. (2006) proposed a random ice force function model, simplifying the ice load to a random peak and periodically distributed isosceles triangle. In this function, the time from loading to unloading is one-third of the entire period (as shown in the Figure 4).

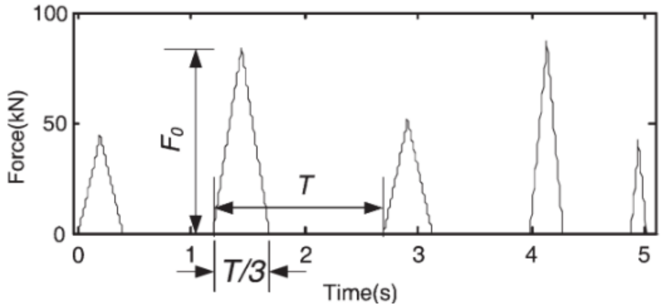

Figure 4. Simplified ice force model on the conical structure

$$f_i(t)=\begin{cases}\frac{6F_{0i}}{T_i}t & 0<t<\frac{T_i}{6}\\ 2F_{0i}-\frac{6F_{0i}}{T_i}t & \frac{T_i}{6}<t<\frac{T_i}{3}\\ 0 & \frac{T_i}{3}<t<T_i\end{cases} \tag{12}$$

Where $f_i(t)$ is the ice load function for the *i*-th ice load cycle; F_{0i} is the amplitude of the ice load for that cycle; T_i is the *i*-th ice load cycle. The ice load cycle is the ratio of the ice failure length to the ice speed.

$$T=\frac{l_b}{v} \tag{13}$$

3.3 Load analysis

Based on the measured statistics of each ice area of Bohai Sea, the maximum design ice thickness of Bohai Sea of 0.5m was selected as the simulation condition to study the ice induced vibration of the structure. In this paper, only the effect of level ice is considered, so the ice thickness is the ice thickness of level ice.

Based on the established ice force models for vertical and conical structures, dynamic ice force time series were generated for both structures. For vertical structures, ice forces were generated using ice force spectrum under extreme ice forces, ignoring spatial coherence, resulting in ice force time series curves. The generated dynamic ice force time course is shown in Figure 5and Figure 6.

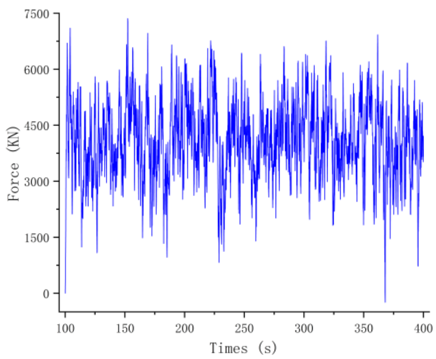

Figure 5. Ice force time series of the vertical structure

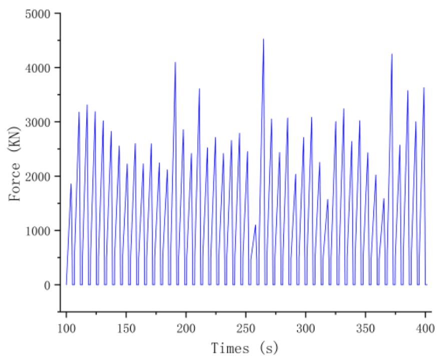

Figure 6. Ice force time series of conical structures

The wind load is selected to be 20.5 m/s at the one-year wind speed in the Bohai Sea to simulate the structural vibration response of the wind-ice combination of the wind turbine under the power generation condition. Assuming that the wind load and ice load are independent, the ice load direction is the same as the wind load direction, and the influence of tidal flow on ice speed is ignored. Using the open source turbulent wind random simulator TurbSim developed by the American Renewable Energy Laboratory (NREL) to generate the global flow wind field suitable for the offshore wind turbine simulation analysis, Simulated vector time series in three directions satisfying the statistical characteristics of the wind speed sequence, Inverse Fourier transform is used to transform the wind speed power spectrum in the frequency domain into the time domain, 3 D turbulent winds at multiple points in space according to the spatial coherence function, To calculate the wind load at the hub, The pulsating wind velocity spectrum adopts the Kaimal spectrum, The average wind speed at the hub is 20.5 m/s, The longitudinal turbulence intensity at the hub is 14%.

4. ICE-INDUCED VIBRATION ANALYSIS OF WIND TURBINE STRUCTURE

4.1 Structural Response Analysis Under Ice Loads Alone

This section focuses on the structural response of ice load alone. We focus on the response of the structure at the following locations: nacelle acceleration, tower tip displacement, and displacement at the location of the ice load, and draw appropriate conclusions about the structural response.

According to the results of the numerical model, in Figure 7, for the 15MW offshore monopile wind turbine, the structural response of the wind turbine with IBCs and the wind turbine without IBCs is not much different, and the IBCs will not reduce the vibration response of the ice load to the structure to much extent. Simulation results reveal that while IBCs effectively reduce peak ice loads by inducing bending failure in the ice, their impact on reducing structural vibration amplitudes is limited. The main reason for this may be the periodic ice loads that can be induced by the intermittent collision of ice with the conical structure, where the dynamical characteristics of the cone ice forces become particularly prominent and the structural dynamics amplification factor is greater.

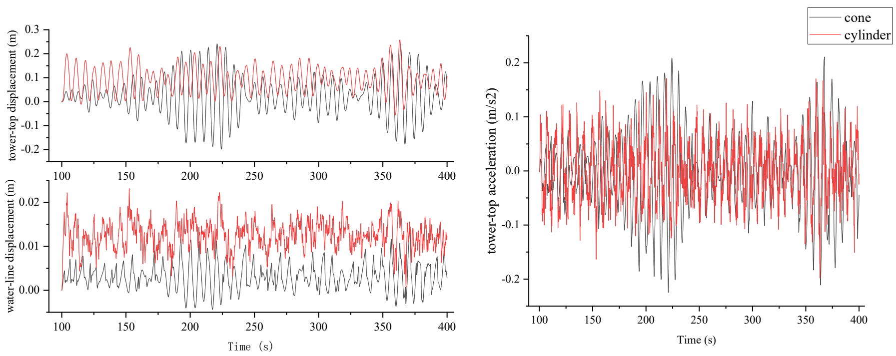

Figure 7. Comparison of the structural responses under ice loading

Table 4. Response under ice loading

	Tower Top Maximum Displacement (m)	Tower Top Average Displacement (m)	Waterline Maximum Displacement (m)	Waterline Average Displacement (m)	Tower Top Maximum Acceleration (m/s²)
CBR	0.257	0.093	0.023	0.010	0.181
cone	0.241	0.065	0.015	0.004	0.201

4.2 Structural Response Analysis Under Combined Wind and Ice Loads

In coastal high-rise structures, wind loads may constitute up to 15% of the total structural load (Hou and Jafari, 2020). Consequently, in analyzing the complex environmental loads on wind turbines, it is imperative to calculate the aerodynamic loads accurately. For offshore wind turbines operating in ice areas, the joint action of wind and ice loads is the key to analyze their structural response. By analyzing the dynamic response of the wind turbine structure under the combined action of wind and ice, it is found that the results of the structural response of the two structural form models are basically the same, as shown in Figure 8. Compared with the ice load, the wind load has significantly more influence on the wind turbine structure and is the main control load.

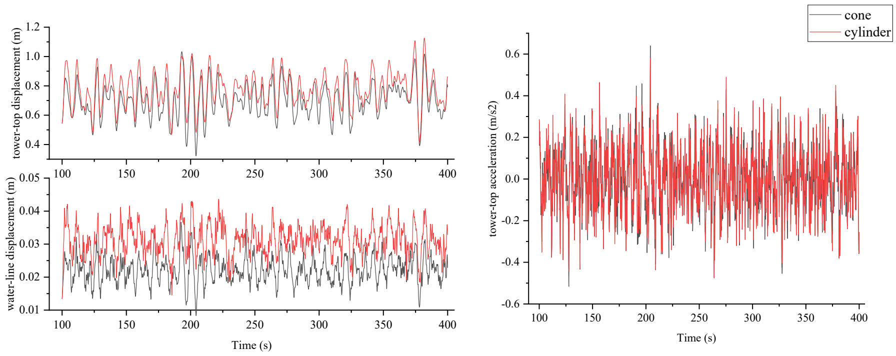

Figure 8. Structural response under the combined ice loading and wind loading

Table 5. Response under combined wind and ice loading

	Tower Top Maximum Displacement (m)	Tower Top Average Displacement (m)	Waterline Maximum Displacement (m)	Waterline Average Displacement (m)	Tower Top Maximum Acceleration (m/s²)
CBR	1.126	0.759	0.043	0.031	0.619
cone	1.055	0.728	0.037	0.023	0.629

CONCLUSIONS

This study analyzed the structural response of a 15MW monopile wind turbine under ice loads and combined wind-ice loads, comparing the ice-induced vibration responses of a 15MW monopile offshore wind turbine with and without ice-breaking cones. The results show that although ice-breaking cones can reduce ice load amplitudes by transforming the ice failure mode into bending failure, they have limited impact on improving the vibration response of large-capacity wind turbine structures. Compared with the ice load, the wind load has a greater impact on the wind turbine structure.

With the application of large-capacity OWTs, the diameter of the tower is increasing, and the diameter of the IBCs also increases, which will increase the ice load sharply. And the large-capacity monopile wind turbine structure has the characteristics of long vibration period and larger horizontal stiffness, the occurrence of the probability of FLI is small. In addition, the width of the waterline of the structure after adding the cone increases, and the wave load on the structure increases. Therefore, it is suggested that for large-capacity monopile offshore wind turbines, the use of IBCs may not offer significant vibration mitigation benefits and could be omitted to optimize cost and structural performance.

In this study, we only considered the influence of dynamic load on the wind turbine structure under extreme conditions, but not the ice vibration fatigue analysis of the structure. At the same time, we ignored the effect of pile and soil action on the dynamic response performance of the monopile wind turbine. Further research in the subsequent work requires further research and analysis. This study provides a reference for the anti-icing design of large-capacity OWTs in ice-covered areas. However, in practical engineering applications, a comprehensive assessment considering the randomness of environmental parameters and long-term fatigue effects is necessary.

REFERENCES

Barker, A., Sudom, D., & Sayed, M. 2014. Conical structures in ice: the roles friction, slope and shape play. In: OTC Arctic Technology Conference: OTC-24566. OTC.

Bekker, A.T., Sabodash, O.A., SeJiverstov, V., Koff, G., Pipko, E., 2009. Estimation of limit ice loads on engineering offshore structures in the Sea of Okhotsk. Proc. 19th International Offshore and Polar Engineering Conference (ISOPE), Osaka, Japan, June 21–26.

Gaertner, E., Rinker, J., Sethuraman, L., et al., 2020. IEA Wind TCP Task 37: Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine.

Guojun W., Dayong Z., & Chunjuan L., 2016. Vibration analysis of offshore wind turbine foundation in ice zone. Ship and Ocean Engineering, 45, pp.109–113.

Hammer, T. C., Willems, T., & Hendrikse, H., 2023. Dynamic ice loads for offshore wind support structure design. Marine Structures, 87, 103335. Available at: https://doi.org/10.1016/j.marstruc.2022.103335 .

Hammer, T.C., & Hendrikse, H., 2024. Hardware-in-the-loop experiments in model ice for analysis of ice-induced vibrations of offshore structures. Scientific Reports, 14(1), p.18327.

Hammer, T.C., Owen, C.C., van den Berg, M., & Hendrikse, H., 2022. Classification of ice-induced vibration regimes of offshore wind turbines. In: International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Vol. 85918, p.V006T07A021.

Hendrikse, H., & Nord, T., 2019. Dynamic response of an offshore structure interacting with an ice floe failing in crushing. Marine Structures, 65, pp.271-290.

Hendrikse, H., Hayo, S., Seidel, M., Metrikine, A., & Løset, S., 2017. Initial results of a study into the estimation of the development of frequency lock-in for offshore structures subjected to ice loading.

Hou, F., & Jafari, M., 2020. Investigation approaches to quantify wind-induced load and response of tall buildings: a review. Sustain. Cities Soc., 62, p. 102376.

Huang, Y., Ma, J. & Tian, Y., 2013. Model tests of four-legged jacket platforms in ice: Part 1. Model tests and results. Cold Regions Science and Technology, 95, pp.74–85.

ISO 19906, 2019. Petroleum and Natural Gas Industries - Arctic Offshore Structures.

Ji, S., & Yang, D., 2022. Ice loads and ice-induced vibrations of offshore wind turbine based on coupled DEM-FEM simulations. Ocean Engineering, pp.110-197.

Jussila, V. & Heinonen, J., 2012. Comparison of ice-induced vibrations on a conical and a cylindrical offshore wind turbine substructure. In 21st IAHR International Symposium on Ice, pp. 998-1013.

Jussila, V., Popko, W. & Heinonen, J., 2013. Interfacing of ice load simulation tools for cylindrical and conical structure with OneWind simulation tool for offshore wind turbines. In 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, POAC 2013, Aalto University.

Kärnä, T., et al., 2007. An upper bound model for self-excited vibrations. In Proceedings of 19th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), pp.177-189.

Kärnä, T., Qu, Y., Bi, X., Yue, Q., & Kuehnlein, W., 2007. A spectral model for forces due to ice crushing. Journal of Offshore Mechanics and Arctic Engineering, 129(2), pp.138-145. Available at: https://doi.org/10.1115/1.2426997

Kärnä, T., Izumiyama, K., Yue, Q., Yan, Q., Guo, F., & Xu, N., 2007. An upper bound model for self-excited vibrations. In: Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), pp.177-189.

Kärnä, T., Qu, Y., & Kuhnlein, W., 2004. A New spectral method for modeling dynamic ice actions. In Proceedings of the 23rd International Conferences on Offshore Mechanics and Arctic Engineering, Vancouver, Canada, 20-25 June, OMAE2004-51360, ASEM, pp.8-16.

Kuutti, J., Kolari, K., & Marjavaara, P., 2013. Simulation of ice crushing experiments with cohesive surface methodology. Cold Regions Science and Technology, 92, pp.17-28.

McCoy, T.J., Brown, T.R., & Byrne, A.R., 2014. Ice Load Project Final Technical Report. [Note: Assuming it's a report; if it's a book, move to Books section]

Sanderson, T.J.0., 1988, Ice Mechanics: Risks to Offshore Structures, Graham and totta. London，p.253、0-86010-785-X

Seidel, M., & Hendrikse, H., 2018. Analytical assessment of sea ice-induced frequency lock-in for offshore wind turbine monopiles. In: Marine Structures, 60, pp.1-18. [Note: Though originally a journal, included here due to conference-like presentation]

Song, M., Shi, W., Ren, Z., & Zhou, L., 2019. Numerical study of the interaction between level ice and wind turbine tower for estimation of ice crushing loads on structure. Journal of Marine Science and Engineering, 7(12), pp.1-23.

Tang, Y., Shi, W., You, J. & Michailides, C., 2021. Effects of nonlinear wave loads on large monopile offshore wind turbines with and without ice-breaking cone configuration. Journal of Marine Science and Technology, 26(1), pp.37–53.

van der Stap, F.L., Nielsen, M.B., Owen, C.C., et al., 2023. On the feasibility of monopile foundations for offshore wind in the Baltic Sea. In POAC 2023: 27th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC.

Wang, B., Liu, Y.Z., Zhang, J.H., Shi, W., Li, X., & Li, Y., 2022. Dynamic analysis of offshore wind turbines subjected to the combined wind and ice loads based on the cohesive element method. Front. Mar. Sci., 9.

Wang, B., Gao, S., Qu, Y., Yin, H. & Chuang, Z., 2023. Mechanism of Phase-Locked Ice Crushing against Offshore Structures. Journal of Marine Science and Engineering, 11(4), p.868.

Wang, B., Yin, H., Gao, S., Qu, Y., & Chuang, Z., 2024. Ice-induced vibration analysis of fixed-bottom wind turbine towers. Journal of Marine Science and Engineering, 12, p.1159.

Xu, N., 2011. Research on Ice Force of Conical Offshore Structures. Dalian University of Technology, Dalian, China.

Xu, N., Yue, Q., Qu, Y., Yuan, S., & Liu, X., 2014. Comparison and cause analysis of ice-induced structural vibration of upward and downward cones. In: ISOPE International Ocean and Polar Engineering Conference: ISOPE-I. ISOPE.

Yan, Q., Qianjin, Y., Xiangjun, B. & Tuomo, K., 2006. A random ice force model for narrow conical structures. Cold Reg. Sci. Technol., 45, pp.148–157.

Ye, K., Li, C., Yang, Y., et al., 2019. Research on influence of ice-induced vibration on offshore wind turbines. Journal of Renewable and Sustainable Energy, 11(3).

Yin, H., Wang, B., Gao, S., Chuang, Z., Qu, Y., & Chen, D., 2023. Ice-induced frequency lock-in vibration analysis of bottom fixed wind turbine structure. In: OMAE2023 Conference Proceedings, pp.1-10. [Note: Adjusted based on typical conference paper inclusion within journal articles format]

Zhang, J. & Wang, H., 2022. Development of offshore wind power and foundation technology for offshore wind turbines in China. Ocean Engineering, 266, p. 113256.

Zhu, B., Sun, C. & Jahangiri, V., 2021. Characterizing and mitigating ice-induced vibration of monopile offshore wind turbines. Ocean Engineering, 219, p.108406.

Zou, P., Bricker, J.D., Fujisaki-Manome, A., et al., 2024. Characteristics of ice-structure-soil interaction of an offshore wind turbine. Ocean Engineering, 295, p. 116975.