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Risk assessment of sea ice disasters on fixed jacket platforms in the Liaodong Bay

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Abstract. Sea ice disasters seriously threaten the safety of oil platforms in the Bohai Sea. Therefore, it is necessary to carry out the risk assessment of sea ice disasters on oil platforms in the Bohai Sea. In the study, the risk assessment of sea ice disasters on fixed jacket platforms in the Liaodong Bay was performed. Firstly, the formation mechanisms of sea ice disasters were analyzed and the sources and modes of sea ice risks were clarified. Secondly, according to the calculation formulas of extreme ice force, dynamic ice force and accumulated force, several ice indices such as thickness, motion, strength, period, and concentration were proposed as the hazard indices and corresponding values were assigned to the proposed indices based on ice conditions in the Bohai Sea. Thirdly, based on four structural failure modes (structures overturned by the extreme ice force (Mode 1), structural fracture failure caused by dynamic ice force (Mode 2), facility damage caused by the dynamic ice force (Mode 3), and structural function failure caused by accumulated ice (Mode 4)), the structural vulnerability index, overturning index, dynamic index, ice-induced vibration index, and function index were proposed and corresponding values were assigned to the structural vulnerability index of fixed jacket platforms in the Liaodong Bay. Fourthly, the weight of each risk index was determined according to previous sea ice disasters and accidents and the sea ice risk was calculated with the weighted synthetic index method. Finally, with the above index system and risk assessment methods, the risk assessment of sea ice disasters on 10 jacket platforms in three sea areas in the Liaodong Bay was carried out. The analysis results showed that efficient sea ice prevention strategies could largely mitigate the sea ice-induced vibration-related risks of jacket platforms in the Liaodong Bay. If steady-state vibration occurred (usually in front of the vertical legged structure) or the structural fundamental frequency was high, the structural vulnerability was significantly increased and the calculated risk levels were high. The sea ice risk assessment method can be applied in the design, operation, and management of other engineering structures in sea ice areas.

1 Introduction

In recent years, the losses caused by sea ice disasters have increased significantly (Fang et al., 2017). In China, sea ice disasters mainly occur in the Bohai Sea and the North Yellow Sea. Sea ice can push down offshore platforms, destroy ships and offshore engineering facilities, impede navigation, and cause losses to offshore and tidal aquaculture (Zhang et al., 2013; Wang et al., 2011; Lu, 1993; Ding, 2000). In the ice period of 1969, the entire Bohai Sea was covered by sea ice and ice thickness even reached 60 cm. In the sea ice disaster, the No. 2 living and drilling platforms collapsed due to the huge thrust of sea ice, thus leading to a great impact on the economy of China. In 1977, the beacon tower of No. 4 drilling well was also pushed down by sea ice. On January 28, 2000, the JZ20-2 MS Platform suffered severe steady-state vibration under the action of level ice, thus causing the fatigue fracture of the evacuation pipeline of the No. 8 well, natural gas leakage, and platform suspension (Yue et al., 2009; Li et al., 2008, Timco et al., 2011). Since 2010, the aquaculture area affected by sea ice disasters has reached 40,000 hectares per year (State Oceanic Administration, 2011-2016).

Since the 1980s, Chinese scholars studied the preventive measures of sea ice disasters (Ouyang et al., 2017; Lu et al., 1993; Wang et al., 2011; Zhang et al. 2015), sea ice measurement and forecast (Luo et al., 2004; Zhao et al., 2014; Su and Wang, 2012), engineering coping strategies (Zhang et al., 2010, 2016), and mechanisms (Yue et al., 2009; Li et al., 2008, Liu et al., 2009; Huang and Li, 2001; Wang et al., 2018; Yue et al., 2007a). Most studies on existing sea ice risk assessment only involved the descriptions of sea ice. Guo Qiaozhen et al. (2008) proposed three sea ice parameters of thickness, strength and period as the influencing factors of sea ice disasters and established three sea ice disaster risk levels, such as zero risk, low risk, and high risk. Gu et al. (2013) converted sea ice thickness into a sea ice hazard index and determined sea ice hazard risk grades. However, due to the differences in the classification results of sea ice disasters on different offshore engineering structures and dominant sea ice factors, the sea ice data required in the assessment of structural ice disaster are different. Therefore, previous results cannot meet the application requirements.

This paper focuses on the risk assessment methods of sea ice disasters on jacket platforms. The hazard indices of sea ice were firstly determined according to the forms of sea ice force on platform structures. Then, the weight coefficients of these indices were determined with ice force calculation formulas. Then, the physical vulnerability index was determined according to the platform failure modes and the weight of the vulnerability index was determined based on the previous sea ice disasters and accidents. Sea ice disaster risks on 10 jacket platforms in three sea areas were respectively assessed with the overall risk assessment method and the multi-mode risk assessment method. Except that several auxiliary platforms are in the high risk level, other platforms are in good condition, but the safety management in winter should be further enhanced.

2 Research area

The Bohai Sea is a seasonal ice-covered sea in the latitude range of 37° and 41° N. It is also the ice-covered sea with the lowest latitude in the northern hemisphere. Liaodong Bay in the Bohai Sea is the most severely iced bay with the ice period of about 130 days. The edge of the ice-covered region is near the contour line of 15 m and about 70 nautical miles away from the top of the bay. Generally, ice thickness is 30-40 cm. The sea ice drifting speed is generally 0.5 m/s and the maximum speed is about 1.5 m/s. The dominant wind in winter is northerly wind. Due to clockwise flow along the coast and the right-turning tide, sea ice conditions in the east are more serious than those in the west. In addition, the warm current from Yellow Sea flows through the northern Bohai Strait into the Bohai Sea, and then to the west bank of Liaodong Bay roughly along the northwest direction, thus raising the water temperature in the western part of the Liaodong Bay. Therefore, sea ice conditions in the west of the Liaodong Bay are more serious than those in the east.

According to the distribution characteristics of sea ice in China, the Bohai Sea and the North Yellow Sea were divided into 21 regions in such a way that the ice conditions in each region were basically the same. Then, the design parameters of marine structures in the 21 regions areas were proposed, including physical and mechanical parameters as well as key parameters of ice conditions (period, thickness and motion). The sea ice parameters in each ice region provide a useful reference for the design of ice structures and the fatigue life assessment of existing structures.

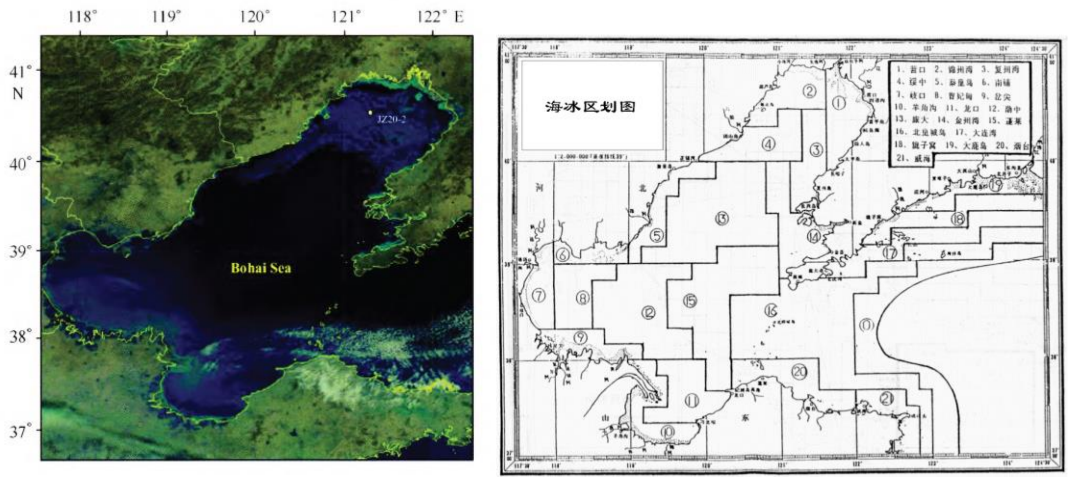

Fig. 1. Location map of Bohai Sea and North Yellow Sea.

Oil platforms in Bohai Sea have two structural forms: caisson structure and jacket structure. The latter is the dominant structure. In addition to the multi-legged structures (usually 4 legs, as shown in Fig. 2(a)), the single-legged structure has been widely applied in auxiliary platforms (Fig. 2(b)) and even main platforms (Fig. 2(c)). In oil platforms, ice-breaking cones are generally adopted to reduce the impact of sea ice. Old platforms had been installed with ice-breaking cones (Fig. 2(d)) and new platforms were designed as the cone form (Fig. 2(e)). Due to the difference in ice conditions, structural form, dynamic performance, function and structural ice resistance, platform structures in the Liaodong Bay showed significant differences in sea ice risk levels. Current sea ice management measures in winter effectively reduced sea ice risks in oil and gas exploitation.

(a) Four-legged oil production platform (built in 1987); (b) One-legged auxiliary platform (built in 1999); (c) One-legged oil production platform (built in 2003).

(d) Three-legged upright pile production platform (built in 1997); (e) Three-legged upright pile production platform with cones (built in 2000)

Fig. 2. Main structural forms of jacket platforms in the Bohai Liaodong Bay.

Oil platforms are dense in the Liaodong Bay, especially the narrow form of jacket structures. The impact of sea ice is significant in the Liaodong Bay. Therefore, it is necessary to carry out the risk assessment of sea ice disaster on jacket oil platforms in the Liaodong Bay.

3 Research methods

3.1 Technical routes

According to the assessment method of natural disaster risks (Zhang et al., 2007; Tachiiri, 2012), the technical routine of the risk assessment of sea ice disasters on oil platforms was established below (Fig. 3).

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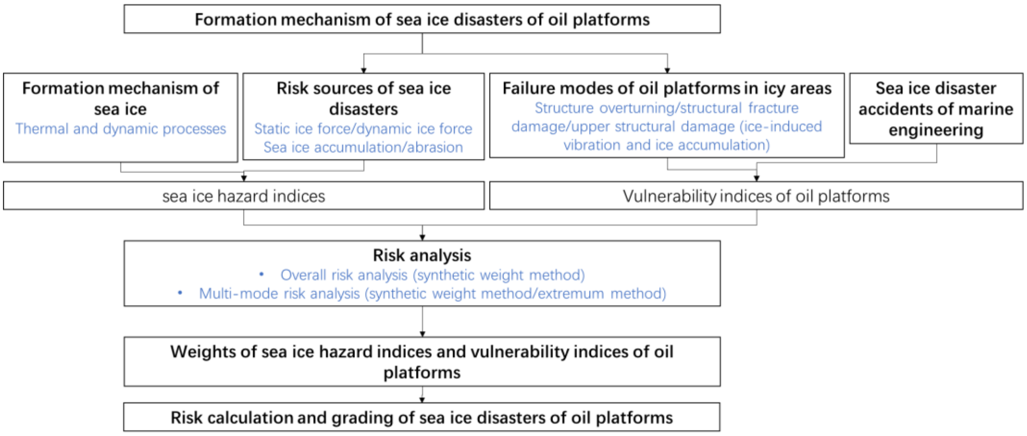

Fig. 3. Flow chart of risk assessment of sea ice disasters on oil platforms.

3.2 Risk assessment model index system

According to the synthetic index method, the sea ice risk assessment index system of oil platforms was established with the risk calculation model (Risk = F (Hazard, Vulnerability, Resistance)) to calculate the risk. Firstly, the hazard index (H), vulnerability index (V), and resistance index (R) were graded and corresponding values were assigned to these indices. Then the sea ice hazard index was qualitatively described as 5 levels: extremely high, high, medium, low, and extremely low and the corresponding quantitative values were respectively set to be 5, 4, 3, 2, and 1. The structural vulnerability index and the resistance levels were described qualitatively as 3 levels: high, medium and low and the corresponding values were set to be 5, 3, and 1, respectively.

Sea ice disasters on oil platforms have different risk modes. Therefore, in the establishment of risk assessment index systems and evaluation models, two methods can be adopted: overall risk assessment and multi-mode risk assessment. According to the overall risk assessment method, the weights of secondary indices are determined to calculate the hazard index (H), vulnerability index (V), and resistance (R) and then the overall risk I_e is calculated according to Eq. (1). According to the multi-mode risk assessment method, the assessment results of various risk modes $I_{s,i}$ are determined with the hazard index H_i, the vulnerability index V_i, and the disaster resistance ability index R_i of various risk modes (Eq. (2)). Then, with the cumulative weight coefficient of various risk modes, the overall risk I_e is calculated or the highest risk level $I_{s,max}$ is selected (Eq. (3)).

$$I_e = HVR = \sum \omega_i H_i \sum \omega_j V_j \sum \omega_k R_k \quad , \tag{1}$$

where I_e is the overall risk assessment result; H, V, and R are respectively the overall hazard, vulnerability, and disaster resistance ability indices; *i*, *j*, and *k* are respectively the numbers of H, V, and R secondary indices; H_i , V_j, and R_k are the secondary indices; ω_i, ω_j, and ω_k are respectively the weight coefficients of these secondary indices.

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$$I_s = \sum \lambda_i I_{s,i} \quad , \tag{2}$$

$$I_{s,max} = max I_{s,i} \quad , \tag{3}$$

where I_s is the calculation result of the multi-mode risk assessment method; $I_{s,max}$ is the calculation result with the maximum risk value according to the multi-mode risk assessment; $I_{s,i} = H_i V_i R_i$ is the calculation result of the *i*-th risk mode; λ_i is the weight of the *i*-th risk mode.

4 Establishment of the risk assessment index system of sea ice disasters

4.1 Formation mechanisms of sea ice disasters

The impact of sea ice is the main cause for accidents and risks of marine structures in ice-covered areas. The impact energy mainly comes from the interactions between wind, currents, thermal expansion and sea ice (Sanderson, 1988). Sea ice disasters have three major risk sources (extreme ice force, dynamic ice force, and sea ice accumulation) and four structural risk modes (structures overturned by extreme ice force, structural fatigue damage induced by ice vibration, upper facility damage by ice vibration, and facility damage due to ice pile climbing).

4.1.1 Risk sources of sea ice disasters and major sea ice risk factors

4.1.1.1 Extreme ice force

When sea ice contacts with a structure and maintains its integrity, sea ice exerts a relatively stable ice force on the structure. Extreme ice force generates static effects and transient impacts. In the sea areas around oil platforms in the Liaodong Bay, sea ice flow rate can reach 1.4 m/s and extreme ice force is directly affected by sea ice thickness, sea ice strength and structural width. The calculation methods of static ice force are given in various engineering design standards of cold zones. For example, when ice is crushed in front of a structure, the ice load generated on the structure can be calculated as follows:

$$F_c = mIf_c \sigma_c DH, \tag{4}$$

where F_c is extrusion ice load; *m* is shape factor and set as 0.9, 1.0 and 0.7 respectively for circular section, square section with positively applied ice load and square section with obliquely applied ice load; *I* is the embedding coefficient; f_c is the contact coefficient; σ_c is the uniaxial compression strength of level ice in the horizontal direction, MPa; *D* is structural width; *H* is the designed level ice thickness.

The horizontal component of ice bending load applied on a slope structure is:

$$F_H = K_\alpha H^2 \sigma_f tan\beta, \tag{5}$$

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where F_{H} is the horizontal component of ice bending load applied on a slope structure; K_{α} is the coefficient related to the structure and ice thickness; H is the designed level ice thickness; σ_{f} is bending strength of level ice; β is the angle (°) between the structural slope and the horizontal plane.

4.1.1.2 Dynamic ice force

When sea ice continuously passes through a structure, it will generate a periodic impact load on the structure, namely, dynamic ice force. Dynamic ice force usually occurs on narrow structures. Under the action of dynamic ice force, a structure will undergo vibration, namely, ice-induced vibration. When the frequency of dynamic ice force is consistent with the structural frequency, it will cause strong vibration due to resonance. Based on the measured ice force time history, the ice force calculation method is proposed. Ice force amplitude and ice force period are important parameters in the calculation. Ice force amplitude can be calculated based on the calculation method of extreme ice force. The recommended calculation method of ice force period is provided in Eq. (6).

Fig. 4. Time history curve of dynamic ice force on a typical coned structure.

Ice period can be calculated as follows:

$$T = l_b / v, \tag{6}$$

where T is ice force period; l_{b} is breaking length of ice plate and affected by ice thickness, ice strength, structural diameter, and ice velocity; v is ice velocity.

4.1.1.3 Sea ice accumulation

After floe is applied on a structure and then broken, if broken ice is not removed in time due to structural blockage, ice accumulation will occur. Usually, the accumulation of broken ice occurs in front of a wide structure or in the vicinity of dense ice-collecting members, such as spacing casing group of the pile leg of an oil platform and the coarse grid at the water intake port of a nuclear power plant. The growth, size, and load of accumulation ice had been extensively explored. The calculation methods of extreme ice force in various specifications also involve ice accumulation. Sea ice accumulation height is calculated as follows:

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$$H = 3 + 4h \ , \quad (7)$$

$$H = 7.6h^{0.64}, \quad (8)$$

where h is level ice thickness.

4.1.2 Sea ice risk modes and key structural parameters of oil platforms

4.1.2.1 Extreme ice force may cause overall structural failure

When the overall deformation of a structure exceeds its allowable deformation under extreme ice force, structural stiffness failure occurs. When extreme ice force exceeds the ultimate bearing capacity of a structure, the structure may be unstable.

4.1.2.2 Ice-induced vibration may cause structural fatigue failure

Structural fatigue damage is caused by a stress repeatedly applied at hot spots of a pipe joint. Structural hot spots will fail after the significant stress (S) has been applied for the specified times (N). Long-term ice-induced structural fatigue damage may decrease the structural resistance and even cause the structural failure due to insufficient structural resistance. In general, conventional ice loads with a higher probability cause a greater damage to a platform structure, whereas extreme ice loads with a lower probability have a smaller effect on the platform.

4.1.2.3 Dynamic ice force may lead to the function failure of facility and affect personnel safety

The strong ice-induced vibration of a structure directly affects its upper facility. In such a vibration, the platform deck is equivalent to the vibration table and can cause the whiplash effect on the upper components. Especially, ice-induced vibration may lead to the direct damage to the key functional facility or components without anti-vibration capability. Natural gas pipelines are distributed on the upper part of platforms for producing natural gas. Due to the long-term ice-induced vibration, connecting parts of these pipelines may be loosened, thus causing natural gas leakage, pipeline breaking and even explosion. The impacts of ice-induced vibration on workers include slight impact, reduced comfort, reduced efficiency, and affected health.

4.1.2.4 Sea ice accumulation may cause the damage to the upper facility or buildings

Sea ice accumulation will increase the application area of ice force on marine structures as well as ice force itself. If sea ice climbs to a structure at a certain height from the ice surface along accumulated ice, it may cause the damage to the upper facility or buildings. If sea ice climbs to a dam, it will destroy onshore buildings. If sea ice climbs to the underlying cable aisle of a platform, sea ice may crush the fence and affect the overall structural stability.

4.2 Hazard index system

4.2.1 Determination of hazard indices based on the risk analysis of sea ice disasters

Based on the relationships among sea ice parameters and their contributions to ice force, the key sea ice hazard indices were proposed (Table 1). Short-term sea ice hazard indices that play a key role in the failure of the platform structure include thickness, velocity, and strength. The long-term sea ice hazard indices related to the time and frequency of sea ice load include ice period and sea ice concentration.

Table 1. Sea ice hazard indices.

Index types	Indices	Criteria
Short-term sea ice hazard indices	Ice thickness, ice velocity, and ice strength	Indices that play a key role in the failure of the platform structure
Long-term sea ice hazard indices	Ice period and sea ice concentration	Indices related to the time and frequency of sea ice load

4.2.2 Sea ice hazard indices

According to Technical Guidelines for Risk Assessment and Zoning of Sea Ice Disasters, sea ice hazard indices were graded. The study area was divided into 21 regions and the values of the indices in each region were mainly determined based on the China Sea Ice Conditions and Application Regulations (Q/HSn 3000-2002). Since the designed life of the oil platform in Bohai Sea was 100 years, a return period of 100 years was selected in the subsequent analysis.

Table 2. Grading of sea ice hazard indices.

Index code	Indices	Index range	Extremely high hazard (5 points)	High hazard (4 points)	Medium hazard (3 points)	Low hazard (2 points)	Extremely low hazard (1 point)
H1	Designed ice thickness, cm	8~41.7	>35	[35,25)	[25,10)	[10,5)	≤5 cm
H2	Designed ice velocity, cm • s^{-1}	0.7~1.9	>1.4	[1.4,1.2)	[1.2,1.0)	[1.0,0.8)	≤0.8
H3	Designed ice strength, Mpa	1.88~2.37	>2.2	[2.2,2.1)	[2.1,2.02)	[2.02,1.9)	≤1.9
H4	Designed severe ice period, day	30~149	>35	[35,25)	[25,10)	[10,5)	≤5
H5	Maximum ice concentration,%	0~100	>80	[80,60)	[60,40)	[40,20)	≤20

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4.3 Vulnerability indices

4.3.1 Determination of vulnerability indices based on the failure mode of jacket structures

According to typical sea ice disaster risk modes, the structural parameters affecting sea ice disasters are listed (Table 3) and the structural influencing factors are analyzed. The main failure modes of jacket structures includes structure overturning by extreme ice force, structural fatigue damage caused by dynamic ice force, and the damage to the upper facility (including personnel) caused by dynamic ice force. Yue et al (2007b) analyzed the static displacement of typical platforms in the Liaodong Bay under extreme ice force.

Table 3. Sea ice disaster risk modes of oil platforms and corresponding vulnerability indices.

Risk modes	Structural performances	Vulnerability indices
Structure overturning by the extreme ice force	Anti-overturning ability	Geometric size and overall stiffness, see Section 4.2.2.1.
Structural fatigue damage caused by the dynamic ice force	Ice-induced vibration resistance capacity (displacement and strain)	Geometric size and overall stiffness, see Section 4.2.2.2.
The facility damage caused by the dynamic ice force	Ice-induced vibration resistance capacity (acceleration)	Geometric size, overall stiffness, and dynamic parameters (natural frequency dominated), see Section 4.2.2.3.
Structural function failure caused by accumulation ice	Structural function	Structural function, see Section 4.2.2.4

4.3.1.1 Structural overturning by extreme ice force (Mode 1) and structural overturning index

When extreme ice force exceeds the ultimate bearing capacity of a structure, the whole structure will collapse. The overturning index *V1* is proposed below.

Based on functional descriptions of buildings under seismic loads, the damage of a structure under extreme ice load is provided in Table 4.

Table 4. Damages of marine structures under extreme ice loads.

Functional levels	I	II	III	IV	V
Damage states	Basically intact	Slight damage	Medium damage	Severe damage	Collapse
Relative structural deformation	$\Delta < H/500$	$H/500 < \Delta < H/250$	$H/250 < \Delta < H/125$	$H/125 < \Delta < H/50$	$\Delta > H/50$

Note: $\Delta = F/K$, where F is ice force; K is structural stiffness; H is the overall height of the structure.

When the ice force difference is not large (10~100 kN), the overturning index of the platform under extreme ice force is proposed as:

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$$M_1=V_1=K_n/KH, \tag{9}$$

where H is the overall height of the structure; K is structural stiffness and it is set to be 10e7~10e9 for jacket platforms in the Liaodong Bay; K_n is the coefficient related to the structural form (pile) and its values for the one-legged platforms and 4-legged platforms are respectively set to be 1 and 2.

4.3.1.2 Structural fatigue damage caused by dynamic ice force (Mode 2) and structural dynamic index

Structural fatigue damage is caused by a stress repeatedly applied at hot spots of pipe nodes. For jacket structures, the stress applied at hot spots is usually linear with structural dynamic response (Δd), which is proportional to the static loading deformation (Δ=F/K). The proportional coefficient is called the amplification factor γ and directly related to structural natural frequency and ice force frequency. Yue et al. (2007b)) analyzed the dynamic characteristics of anti-ice jacket platforms in the Bohai Sea. For the steady-state vibration of an upright structure, the amplification factor is:

$$\gamma=\frac{1}{\sqrt{(1-r^2)^2+(2\xi r)^2}}. \tag{10}$$

For the random vibration of coned structures, the amplification factor is:

$$\gamma_1=\frac{1}{5\sqrt{(1-r_1{}^2)^2+(2\xi r_1)^2}}, \tag{11}$$

where r_1=ω/ωn=f/fn; ω(f) and ωn(fn) are respectively ice force frequency and structural natural frequency.

The structural dynamic index $V2$ is calculated as:

$$V2=\gamma 1*Ka, \tag{12}$$

where γ1 is dynamic amplification factor and can be calculated with the measured data or frequency ratio (γ1=f(r1,ξ)) according to Eqs. (10) and (11); Ka is the reinforcement coefficient of hot spots, namely, the ratio of the stress at the hot spot before reinforcement to that after reinforcement, and its range is (0,1]. Based on finite element analysis or measured data, in the study, the values of Ka were respectively selected as 0.5 for main platforms and satellite platforms and 1.0 for auxiliary platforms.

Considering the fatigue failure modes of jacket structures under dynamic ice force, with structural overturning index $V1$ and dynamic index $V2$, the structural dynamic value corresponding to structural ice vibration fatigue is expressed as:

$$M2=V1*V2, \tag{13}$$

where $V1$ is calculated according to Eq. (9).

4.3.1.3 Damage to the upper facility (including personnel) caused by dynamic ice force (Mode 3)

In general, the greater deck acceleration leads to the greater vibration amplitude of the facility. If it is believed that a jacket structure can be simplified as a structure with a single degree of freedom (Yue, 2007b), deck vibration is similar to simple harmonic motion and its vibration displacement D, velocity V, and acceleration A can be respectively expressed as:

$$D = \Delta st \times sin(\omega t + \varphi); \quad (14)$$

$$V = \Delta st \times \omega \times cos(\omega t + \varphi); \quad (15)$$

$$A = -\Delta st \times \omega^2 \times sin(\omega t + \varphi). \quad (16)$$

In Mode 2, vibration displacement D corresponding to structural vibration index is the key factor to be considered. In the analysis of Mode 3, structural dynamic parameter, natural frequency *f*, should be additionally considered. The higher structural frequency means the greater acceleration. In addition, the structural function also directly affects the risk level. For example, there are many devices on oil production platforms. The design of manned platforms should pay attention to personnel comfort and their risk is relatively high. Unmanned platforms have a low risk. In summary, structural ice vibration index *V3* and structural function index *V4* are proposed respectively based on natural frequency and structural function as follows:

$$V3=f2, \quad (17)$$

where *f* is the main ice vibration frequency of a platform, the fundamental frequency.

$$V_4 = K_b, \quad (18)$$

where K_b is the structural function coefficient and its values for manned center platforms, unmanned center platforms, and auxiliary function platforms such as the bollard are respectively set to be 1.5, 1.2, and 1.0.

In Mode 3, the vibration and functions of a structure should be considered. The structural vulnerability indices to be considered include overturning index *V1*, dynamic index *V2*, ice-induced vibration index *V3*, and function index *V4*. The ice-induced vibration value M3 is expressed as:

$$M3=V1*V2*V3*V40.5 \quad , \quad (19)$$

where *V1*, *V2*, *V3*, and *V4* are respectively calculated according to Eqs. (9), (12), (17), and (18).

4.3.1.4 Damage to the upper facility of the structure caused by sea ice accumulation (Mode 4)

If sea ice climbs to the platform deck due to sea ice accumulation, it will directly threaten the safety of facility and personnel . Therefore, the vulnerability index mainly considered in Mode 4 is the functional index *V4.*

$$M4= V4 \quad (20)$$

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4.3.2. Vulnerability indices

According to the main distribution ranges of the parameters of jacket platforms in the Liaodong Bay, the above-mentioned structural vulnerability indices proposed based on the sea ice risk modes of oil platforms are graded into three levels: high, medium and low (Table 5).

Table 5. Grading and assignment of structural vulnerability indices.

Index codes	Indices	Index range	High risk (5 points)	Medium risk (3 points)	Low risk (1 point)
V1	Overturning index	[4e-10,7e-9]	>2e-9	[2e-9, 1e-9)	≤ 1e-9
V2	Dynamic index	[2,12]	>4	[4,2)	≤ 2
V3	Ice-induced vibration index	[0.5,5]	>4	[4,1.0)	≤ 1.0
V4	Function index	[1,1.5]	1.5	1.2	1

4.4 Disaster resistance ability index

Emergency monitoring and sea ice management measures are the important factors to be considered in the assessment. The disaster resistance ability index R1 is proposed and graded in three levels (Table 6).

Table 6. Grading and assignment of disaster resistance ability index.

Index code	Index	Invalid I	Partially valid II	Valid III
R1	Disaster resistance ability index	1.0	(0.5, 1.0)	0.5

4.5 Risk assessment method

Before the risk assessment of sea ice disasters, it is necessary to separately determine the index system, assessment models, and grading standards. The index system varies with the evaluation model. The index systems are introduced separately according to the overall risk assessment method and the multi-mode risk assessment method below.

4.5.1 Overall risk assessment method

The weight coefficients of sea ice hazard indices were determined according to the importance of each index in the ice force calculation models (Table 8). The weights of structural vulnerability indices (Table 8) were determined based on the failure modes of sea ice disasters and the probabilities of corresponding risks or accidents (Table 7).

Table 7. Probability of platform failure modes and weight coefficient assignment.

Platform failure modes	Probability	Assessment index assignment	Weight coefficients			
			V_1	**V_2**	**V_3**	**V_4**

Structures overturned by extreme ice force	6%	Overturning index assignment, $M_1=V_1$.	0.06	/	/	/
Dynamic ice force causes structural fatigue damage	60%	Dynamic index assignment, $M_2=V_1*V_2$.	0.3	0.3	/	/
Dynamic ice force causes the damage to the upper facility (personnel) of structures	30%	Ice-induced vibration index assignment, $M_3=V_1*V_2*V_3*V_4^{0.5}$.	0.09	0.09	0.09	0.03
Accumulated ice causes the damage to the upper facility of structures	4%	Function index assignment, $M_4=V_4$.	/	/	/	0.04
Total		100%	0.45	0.39	0.09	0.07

Table 8. Hierarchical structure and weights of sea ice risk assessment factors for overall risk analysis.

Criteria layer	Index codes	Sub-criteria layer	Index codes	Weights
Sea ice hazard indices	H	Designed ice thickness	W1	0.69
		Designed ice velocity	W2	0.02
		Designed ice strength	W3	0.06
		Maximum ice concentration	W4	0.1
		Designed severe ice period	W5	0.13
Structural vulnerability indices	V	Overturning index	Q1	0.45
		Overturning index	Q2	0.39
		Ice-induced vibration index	Q3	0.09
		Functional index	Q4	0.07
Structural resistance	R	Structural resistance index		0.1

4.5.2 Multi-mode risk assessment method (multi-index synthetic risk assessment model)

Firstly, the weights of various risk modes were determined based on the failure modes of sea ice disasters and the probabilities of corresponding risks or accidents. Then, based on risk sources, risk mode assignments, and disaster resistance ability in various failure modes, the weights of the hazard indices, vulnerability indices, and disaster resistance ability indices were respectively determined (Table 9).

Table 9. Hierarchical structure and weights of sea ice risk assessment factors for multi-mode risk analysis.

Criteria layer	Index codes	Sub-criteria layer	Index codes	Weight coefficients	Key index layer	Index codes	Weight coefficients

Structures overturned by extreme ice force (0.06)	R1	Extreme ice force	H1	0.20	Ice thickness	H1.1	0.20
		Anti-overturning capability of a platform	V1	0.30	Structural overturning index	V1.1	0.30
		Disaster resistance ability	R1	1.00	Disaster resistance ability index	R1.1	1.00
Damage to the main structure caused by ice-induced vibration (0.60)	R2	Dynamic ice force and its influencing scope (temporal and spatial distributions)	H2	1.00	Ice thickness	H2.1	0.8
					Ice period	H2.2	0.2
		Anti-overturning capability of a platform	V2	0.60	Structural overturning index	V2.1	0.30
					Dynamic index	V2.2	0.30
		Disaster resistance ability	R1	1.00	Disaster resistance ability index	R2.1	1.00
Damage to the upper facility caused by ice-induced vibration (0.30)	R3	Dynamic ice force and its influencing scope	H3	0.50	Ice thickness	H3.1	0.30
					Ice concentration	H3.2	0.10
					Ice period	H3.3	0.10
		Anti-overturning capability and function of a platform	V3	0.60	Structural overturning index	V3.1	0.18
					Structural dynamic index	V3.2	0.18
					Ice-induced vibration index	V3.3	0.18
					Function index	V3.4	0.06
		Disaster resistance ability	R1	1.00	Disaster resistance ability index	R3.1	1.00
Damage to the facility caused by accumulation ice (0.04)	R4	Ice accumulation	H4	0.50	Ice thickness	H4.1	0.40
					Ice concentration	H4.2	0.1
		Function of a platform	V4	0.08	Function	V4.1	0.08
		Disaster resistance ability	R1	1.00	Disaster resistance ability index	R4.1	1.00

4.6 Assessment calculation method and grading criteria

According to Eqs. (1) to (3) in Section 3.2, the risk was calculated with the overall risk analysis method and then graded into 4 levels. The criteria and results of the risk assessment of sea ice disasters on oil platforms are provided in Table 10.

Table 10. Assessment criteria of the risks of sea ice disasters on the oil platforms in the Bohai Sea.

Risk index	(12, 25]	(9, 12]	(6, 9]	[0.5, 6]
Levels	Severe risk	Moderate risk	Mild risk	Low risk

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5 Case analysis

5.1 Parameters

Taking 10 jacket platforms with different functions in the three regions of Liaodong Bay (JZ20-2, JZ21-1, and JZ9-3) as the cases, sea ice risks were calculated with the above assessment methods. The vulnerability index was determined according to the locations of the three regions and corresponding sea ice parameters (Table 11). The designed and assigned values of the vulnerability indices of the 10 platforms were determined by the basic forms, functions and dynamic parameters of the platforms (Table 12).

Table 11. Designed and assigned values of sea ice hazard indices in case analysis

Indices	Designed ice thickness (H1)		Designed ice velocity (H2)		Designed ice strength (H3)		Designed severe ice period (H4)		Maximum ice concentration (H5)	
Sea regions	Designed values/cm	Assigned values	Designed values /cm • s^{-1}	Assigned values	Designed values /Mpa	Assigned values	Designed values /day	Assigned values	Designed values /%	Assigned hazard values
Sea Region 20-2	41.7	5	1.9	5	2.37	5	85	5	almost 100	5
Sea Region 21-1	40.4	5	1.8	5	2.16	5	53	5	almost 100	5
Sea Region 9-3	36.8	5	1.4	4	2.33	5	72	5	80	5

Table 12-1. Designed and assigned values of structural vulnerability indices in case analysis.

Platforms	No. of legs	Leg forms Cone or Cylinder	Platform functions	Manned/unmanned	Leg coefficients	Static stiffness	Water depth	Amplification coefficient	Ice-breaking coefficient	Natural frequency	Function coefficient
			(Oil recovery/auxiliary function)		kn	K	H	r	Ka	f	Kf
JZ20-2 A	4	cone	Oil recovery	Manned	1.50	2.0E+08	15.60	4.17	0.50	0.87	1.50

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JZ20-2 B	3	cone	Oil recovery	unmanned	2.00	6.4E+07	16.50	4.17	0.50	1.36	1.20
JZ20-2 C	4	cone	Oil recovery	Manned	1.50	9.3E+07	16.50	4.17	0.50	1.41	1.50
JZ20-2 D	1	cone	Oil recovery	Manned	1.00	6.1E+07	13.50	4.17	0.50	1.00	1.50
JZ21-1 E	4	cone	Oil recovery	unmanned	1.50	9.0E+07	15.60	4.17	0.50	1.10	1.00
JZ9-3 F	4	cone	Auxiliary compressor	unmanned	1.50	1.2E+08	9.50	6.00	1.00	2.06	1.20
JZ9-3 G	1	cylinder	Auxiliary mooring pile	unmanned	1.00	1.3E+08	10.00	12.00	1.00	2.32	1.00
JZ9-3 H	4	cone	Oil recovery	Manned	1.50	9.0E+07	9.00	4.17	0.50	1.10	1.50
JZ9-3 I	1	cylinder	Auxiliary mooring pile	unmanned	1.00	5.4E+07	9.00	4.17	1.00	6.40	1.00
JZ9-3 J	1	cone	Oil recovery	unmanned	1.20	2.1E+07	9.00	15.00	0.50	0.84	1.20

Table 12-2. Designed and assigned values of structural vulnerability indices in case analysis.

Platforms	Anti-overturning index		Dynamic index		Ice-induced vibration index		Function index	
uV_1=kn/(KH)	Assigned values	V_2=Ka*r	Assigned values	V_3=f^2	Assigned values	V_4=kf	Assigned values	
JZ20-2 A	4.8E-10	1	2.08	3	0.76	1	1.50	5
JZ20-2 B	1.9E-09	3	2.08	3	1.85	3	1.20	3
JZ20-2 C	9.8E-10	1	2.08	3	1.99	3	1.50	5
JZ20-2 D	1.2E-09	3	2.08	3	1.00	1	1.50	5
JZ21-1 E	1.1E-09	3	2.08	3	1.21	1	1.00	1
JZ9-3 F	1.3E-09	3	6.00	5	4.24	5	1.20	3
JZ9-3 G	7.6E-10	1	12.00	5	5.38	5	1.00	1
JZ9-3 H	1.9E-09	3	2.08	3	1.21	3	1.50	5
JZ9-3 I	2.1E-09	5	4.17	5	40.96	5	1.00	1
JZ9-3 J	6.5E-09	5	7.50	5	0.71	1	1.20	3

5.2 Sea ice risk assessment and grading

According to the overall risk analysis method described in Section 4.4.1, the sea ice hazard (*H*), structural vulnerability (*V*) and disaster resistance ability (*R*) were determined and then the overall risk I_e was calculated according to Eq. (1) and Table

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8. Then, the calculation results of four sea ice risks $I_{s,i}$ (i=1,2,3,4) were determined. According to Eqs. (2) and (3), with the synthetic index method, the multi-mode risk analysis results I_s and maximum risk values $I_{s,max}$ were calculated.

Table 13. Sea ice risk assessment analysis and risk grading results in case analysis.

	Overall risk analysis				Multi-mode risk analysis					
Platforms	H	V	R	Ie=HVR	Is,1	Is,2	Is,3	Is,4	Is,max	Is,c
JZ20-2 A	5	2.06	0.5	5.15	2.5	5	5	12.5	12.5	5.15
JZ20-2 B	5	3	0.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
JZ20-2 C	5	2.24	0.5	5.6	2.5	5	6.5	12.5	12.5	5.6
JZ20-2 D	5	2.96	0.5	7.4	7.5	7.5	6.5	12.5	12.5	7.4
JZ21-1 E	5	2.68	0.5	6.7	7.5	7.5	5.5	2.5	7.5	6.7
JZ9-3 F	4.98	3.96	0.5	9.86	7.5	10	11	7.5	10.5	9.9
JZ9-3 G	4.98	2.92	0.5	7.27	2.5	7.5	8.5	2.5	8.5	7.3
JZ9-3 H	4.98	3.14	0.5	7.82	7.5	7.5	8	12.5	12.5	7.85
JZ9-3 I	4.98	4.72	0.5	11.8	12.5	12.5	12	2.5	12.5	11.8
JZ9-3 J	4.98	4.5	0.5	11.2	12.5	12.5	9	7.5	12.5	11.25

Notes: [red] indicates severe risk; [orange] indicates moderate risk; [yellow] indicates mild risk; [light orange] indicates low risk.

5.3 Analysis results

The three risk calculation results (I_e, I_s, and $I_{s,max}$) were compared (Fig. 5). In the calculation results obtained by the synthetic index method, the overall risk analysis results I_e were basically the same to the multi-mode risk analysis results I_s and the risk grading results were the same because the theoretical basis for establishing the index system and the weight of the secondary indices were the same in the two methods. The risk mode with the higher weight (such as Mode 2) dominated the multi-mode risk analysis results (I_s) obtained with the synthetic index method. When $I_{s,max}$ was largely different from I_e and I_s, the risk values of most of the risk modes (such as Mode 4) with lower weights were higher, such as Platforms A, C, D, and H.

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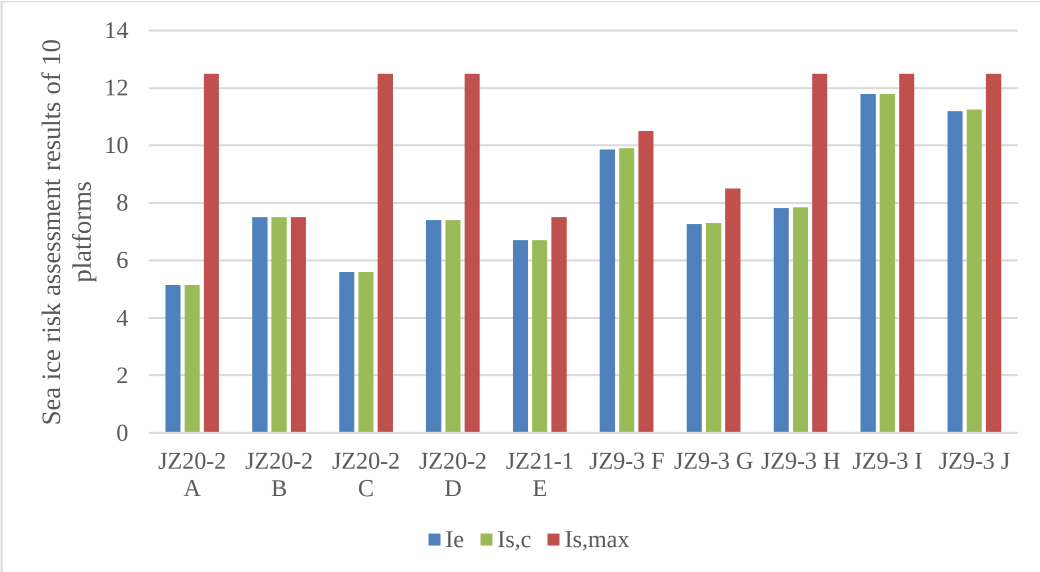

Fig. 5. Comparison of the three risk calculation results (I_e, I_s, and $I_{s,max}$).

According to the overall risk analysis results I_e and the multi-mode risk analysis results I_s, there are two main reasons for the higher risk level. Firstly, the steady-state vibration may occur on the structures and the dynamic larger amplification factor *r* leads to the higher dynamic index V_2. Therefore, the structural fatigue failure related to ice-induced vibration caused by dynamic ice force (Mode 2) occurs on some platforms, such as Platforms F and J. Secondly, due to the high structural fundamental frequency, the structural ice-induced vibration index V_3 is large and the facility function failure caused by ice-induced vibration acceleration (Mode 3) occurs. For example, Platform I has a fundamental frequency of 6.4 Hz, which is significantly higher than the fundamental frequency of common jacket structures in the Liaodong Bay (0.5~2 Hz).

6 Conclusions

In the study, the risk assessment method of sea ice disasters was developed for jacket platforms in ice-covered sea areas in the Liaodong Bay of Bohai Sea. The sea ice risk index system considering sea ice hazard, structural vulnerability and disaster resistance ability was established. In addition, based on the synthetic index method, sea ice disaster assessment methods were constructed, including the overall risk assessment method and multi-mode risk assessment method. The above key indices were determined based on the formation mechanism of sea ice disasters. The weights of these indices are recommended based on sea ice disaster cases. However, the values of these indices were determined based on the ice conditions and parameters of jacket platforms in the Liaodong Bay. The applicability of these values in other sea areas needs to be further verified.

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