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Minimum life-cycle cost design of ice-resistant offshore platforms

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Abstract. In China, the oil and natural gas resources of Bohai Bay are mainly marginal oil fields. It is necessary to build both ice-resistant and economical offshore platforms. However, risk is involved in the design, construction, utilization, maintenance of offshore platforms as uncertain events may occur within the life-cycle of a platform under the extreme ice load. In this study, the optimum design model of the expected life-cycle cost for ice-resistant platforms based on cost-effectiveness criterion is proposed. Multiple performance demands of the structure, facilities and crew members, associated with the failure assessment criteria and evaluation functions of costs of construction, consequences of structural failure modes including damage, revenue loss, death and injury as well as discounting cost over time are considered. An efficient approximate method of the global reliability analysis for the offshore platforms is provided, which converts the implicit nonlinear performance function in the conventional reliability analysis to linear explicit one. The proposed life-cycle optimum design formula are applied to a typical ice-resistant platform in Bohai Bay, and the results demonstrate that the life-cycle cost-effective optimum design model is more rational compared to the conventional design.

Keywords: life-cycle cost; cost-effective design; global reliability; optimal design; offshore platform; ice load.

1. Introduction

The oil and natural gas resources of Bohai Bay in China are mainly marginal oil fields, and there are approximately more than two months of ice covering season every year. The ice force is always the dominant environmental force for the offshore structures. Furthermore, for the ice-resistant platforms in the marginal oil fields, the use of steel for construction should be reduced as much as possible to make more profits in the exploitation of oil and gas. Thus, to design the offshore platforms with both ice-resistant capacity and lower cost is the main task of the designers.

In Bohai Bay, the ocean environment is so complicated that there are many uncertainties in design of offshore platforms, such as the randomness of ice thickness, ice velocity, ice strength, etc. Simultaneously, due to corrosion of the structure materials caused by sea water, the global resistance of the offshore platform is deteriorated over time. Thus, risk, which is determined by both the

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occurrence probability and its consequence of each event of interest, is involved in the design, construction, utilization, maintenance of offshore platforms as uncertain events may occur during the life–cycle of a platform. It is necessary for ice-resistant platforms design in Bohai Bay to pursue both economical and ice-resistant aims by life-cycle cost-effective optimum design, which is the very objective of the present paper.

The concept of performance-based design has caused more and more interest and has undergone a lot of developments in earthquake engineering in recent years, in which cost-effectiveness criterion is one of its most important principle that considers not only the engineering technology factors but also economical, social and political consequences. The design aim is to strike a balance between the initial cost and potential large losses over the structure's lifetime by minimization the expected lifecycle cost. Most of structural optimization of offshore structures up to now focused on the minimum initial cost design with the constraints of the performance requirements specified in the design code. Recently, a few researchers have pursued extensive studies on the issue of optimal design of offshore structures on the basis of minimum expected life-cycle cost, considering structural initial cost, repair cost, and damage cost. Bea *et al.* (1998) generalized the life-cycle risk characteristics of offshore structures, based on reliability and risk assessment, considering internal (natural) and external (artificial) factors. Pinna *et al.* (2003) determined the optimum design of monopod platforms by cost-effective criteria, and considered the economic consequences of failure, and the proportion of fixed cost associated with the construction of the platform. Dimitriv and Stewart (2003) predicted the expected costs of repair and replacement based on a time-variant probabilistic model, and applied it to calculate life-cycle cost for RC structures in marine environments under different exposure conditions. Leon and Ang (2002) proposed a reliability-based cost-benefit optimal decision model for the risk management of oil platforms in the life-cycle, considering the integration of social issues and economics into the management decision process, and formulated the cost functions of the structures (including repair, injury, fatality, indirect loss cost) as functions of the damage level. Garbatov and Soares (2001) emphasized the need for inspections for fatigue failures of floating structures during their lifetime, and proposed to minimize the maintenance costs by a reliability criterion based on the variation of inspection quality. Ang *et al.* (2001, 1997) analyzed offshore structures constructed in Mexico based on cost functions in terms of the deformation and energy as damage index, and applied it to optimum design and reinforce maintenance.

It should be pointed out that the above research efforts focus on the deep-sea platforms with wave as the dominant environmental load, and there are still some issues related to minimum life-cycle cost design for offshore platforms in current research deserving further study. For example, the initial cost is evaluated according to some specified designs rather than to some convenient estimation approach with respect to structural parameters; the evaluation of failure damage costs mainly depend on actual statistical data and are not associated with structural responses induced by environment loads; only the performance requirements of the structure itself are considered and the consequences caused by crew discomfort and facilities damage are not included, etc. On the other hand, the performance function of the global offshore platform structural reliability analysis is usually a highly nonlinear implicit function with respect to the basic design variables, and furthermore a lot of computational efforts are needed.

In this study, the optimum design model to minimize the expected life-cycle cost for ice-resistant platforms based on cost-effectiveness criterion is proposed. Multiple performance demands under ice load, such as those of the structure, facilities and crew members, are treated. The related failure evaluation criteria, costs of construction, consequences of structural failure modes are formulated, in which the damage loss, repair cost, death and injury loss as well as discounting cost over time are considered. And an efficient approximate approach of reliability analysis with the accepted accuracy is the main purpose of the present paper.

2. Performance requirements of ice-resistant offshore platforms

From the viewpoint of research objects, the performance requirements of ice-resistant offshore platforms can be classified into three groups, those of the structure, facilities and crew members. From the viewpoint of mechanical characteristics, the performance requirements can be classified into extreme static and dynamic requirements, due to inherent property of ice load (ISO 1998).

In the current code-based design of offshore platforms, the seismic load, waves, sea current, wind, and ice loads are usually converted into equivalent static actions (SY 10030-2003). The strength, stiffness and stability demands of the structures or components are evaluated under all sorts of equivalent static loads combination to guarantee that the stress, deformation and buckling load are less than their threshold values, respectively. In this study, the strength, stiffness and stability demands of ice-resistant platforms under the extreme static ice load are considered.

3. Formulation of lifecycle cost-effective optimum design

Life-cycle effective optimum design of ice-resistant offshore platforms involves not only the initial cost but also the discounted life-cycle damage costs over the life span of the structure, which requires the assessment of failure probability for all failure modes considered in the cost model. Expected life-cycle cost calculation is an important consideration for applying the cost-effective optimum design of ice-resistant offshore platforms, in which, uncertainties in different performance requirements and cost incurred due to unsatisfactory performance are of major considerations. The initial costs include those of construction, and consequences of structural failure modes are formulated in consideration of the damage loss, repair cost, death and injury loss as well as discounting factor over time. Over a time period of t, the expected total cost is calculated by Wen (2001)

$$E[C(t,X)] = C_0(X) + E\left[\sum_{i=1}^{N(t)}\sum_{j=1}^{k} C_{ij}e^{-\lambda t_j}P_{ij}(X,t_j)\right] \qquad (1)$$

in which $E[\cdot]$ is the expected value; C_0 the initial cost for new structure; X the design variable vector, e.g., design loads and resistance, or load and resistance factors associated with nominal design loads and resistance; t_j the loading occurrence time, a random variable; $N(t)$ the total number of severe loading occurrences over the period of t, a random variable; C_{ij} the cost value of the jth failure mode being reached at time of the ith loading occurrence including costs of damage, repair, loss of service, and deaths and injuries; $e^{-\lambda t_j}$ the discounted factor at time t_j, λ the constant discount rate per year; P_{ij} the probability of the jth failure mode being exceeded given the ith loading occurrence; k the total number of failure modes under consideration, it is reasonable to assume that the number is small.

3.1 Initial cost

A complete estimation of initial cost should include costs from material, design and construction. Initial cost can be evaluated by means of two strategies: (a) the detailed evaluation according to the specific design project when the detailed design available; (b) the global evaluation based on an approximate function of the initial cost with respect to the typical design parameter before the detailed design, such as the structural reliability, design resistance, etc. The former focuses on structural individuality; it can be evaluated easily in detailed design stage. The latter highlights the structural generality; it needs to generalize some approximate relationship from offshore platform structures in the conceptual or initial design stage. In the present paper, the second strategy is used and the initial cost C_0 is expressed as an approximate linear function of the structural global resistance (Kanda and Ellingwood 1991), with the summation of material cost C_m and labor cost C_l. Labor cost is estimated as 60% of the material cost. The initial cost can be written as

$$C_0 = C_m + C_l; \quad C_l = 0.6C_m \tag{2}$$

3.2 Damage costs

For life-cycle cost-effective optimum design, the potential costs of damage from the future risk may arise as a result of exceedance of various critical failure modes that may occur over the life span of the ice-resistant platform under the extreme ice loads. It is so complicated to evaluate damage costs that are closely related to social, economical, political and human factors. Damage costs can be classified into direct and indirect losses, in which the direct loss involves the repair cost, cost of damage to equipment, cost of deferred production, death and injury losses, and the indirect refers to the loss related to social, political, psychological factors caused by the collapse or explosion of the platform.

Assume that the hazard occurrences can be modeled by a simple Poisson process with the constant occurrence rate of per year and the resistance is time-invariant, thus the failure probabilities under a single or multiple hazards are time invariant. From Eq. (1), the expected damage costs of ice-resistant platforms induced by the extreme ice may be expressed as

$$C_{extrem}(T, X) = \frac{v_1}{\lambda}(1 - e^{-\lambda T})\sum_{k=1}^{a} C_{extremk}P_k \tag{3}$$

in which v_1 is the occurrence rates of the extreme static and dynamic ice loads per year; a is the number of failure modes under ice load; $C_{extremk}$ is the damage costs of the kth failure mode; P_k is the probability of the kth failure mode, which can be calculated by

$$\begin{gathered} P_1 = P(\Delta \le \Delta_1) \\ P_k = P(\Delta_{k-1} < \Delta \le \Delta_k) = P(\Delta \le \Delta_k) - P(\Delta \le \Delta_{k-1}) \quad k = 2, \ldots, N-1 \\ P_N = P(\Delta > \Delta_N) \end{gathered} \tag{4}$$

in which Δ and Δ_k are the damage index and damage boundary of the kth failure mode under different ice loads, N is the number of damage intervals.

Based on the damage cost evaluation model provided by Ang and De leon (1997, 2002), damage cost functions of all sorts of failure modes under ice loads can be expressed as the general form

$$C_f = \alpha D^{\beta} \tag{5}$$

where α, β are constants, depending on different failure modes; D is the structure global damage index.

The expected cost of damage includes the cost of the consequences of all potential damages that may occur induced by the extreme static ice load within the life time of the platform. The damage costs will include the cost of repair C_R, the loss of equipment C_E', the deferred production loss C_{DP}, the cost of injuries C_{IN}, the loss associated with fatality C_L, and the indirect losses C_{IL} related to the loss corresponding to platform collapse. Each of the damage cost components will be a function with respect to the damage index.

(1) Repair cost C_R: $\begin{cases} C_R = (R_c/D_R)D & D < D_R \\ C_R = R_c & D > D_R \end{cases}$ (6)

where R_c is the replacement cost, D is the damage index under extreme ice load, D_R is the tolerable or repairable damage index.

(2) Loss of equipment C_E': $\begin{cases} C_E' = C_E D & D < 1 \\ C_E' = C_E & D \geq 1 \end{cases}$ (7)

where C_E is the total cost of the equipment operation on the platform.

(3) Deferred production loss C_{DP}: $\begin{cases} C_{DR} = 0.1{*}P_P{*}T_R{*}P_R{*}D^2 & D < 1 \\ C_{DR} = 0.1{*}P_P{*}T_R{*}P_R & D \geq 1 \end{cases}$ (8)

where P_P is the current price of platform's product, T_R is the estimated time to restore normal production, P_R is platform's production rate. Here assuming that the profit is 10% of P_P, and let $C_P = 0.1{*}P_P{*}T_R{*}P_R$.

(4) Cost of injuries C_{IN}: $\begin{cases} C_{IN} = C_{1I}{*}N_I{*}D^2 & D < 1 \\ C_{IN} = C_{1I}{*}N_I & D \geq 1 \end{cases}$ (9)

where C_{1I} is the cost of an injury N_I is the expected number of injured personnel.

(5) Loss associated with fatality C_L: $\begin{cases} C_L = C_{1L}{*}N_D{*}D^4 & D < 1 \\ C_L = C_{1L}{*}N_D & D \geq 1 \end{cases}$ (10)

where C_{1L} is the cost related to a life lost, N_D is the expected number of fatalities.

(6) Indirect losses C_{IL}: $\begin{cases} C_{IL} = C_{LC}{*}D^4 & D < 1 \\ C_{IL} = C_{LC} & D \geq 1 \end{cases}$ (11)

where C_{LC} is the loss corresponding to platform collapse induced by extreme static ice load.

The assessment of the structural damage is needed in the above cost functions. Under the extreme static ice load, the structure global damage index can be defined (Park and Ang 1985) as

$$D = \frac{x_m}{x_u} + \frac{\beta_0 E}{Q_y \delta_u} \tag{12}$$

Table 1 Structural performance and damage level under extreme ice load

Performance level	Damage state	Global deformation	Damage loss
I	Nearly intact	$\Delta < H/500$	C_R
II	Minor damage	$H/500 < \Delta < H/250$	$C_R + C_E$
III	Moderate damage	$H/250 < \Delta < H/125$	$C_R + C_E + C_{DR} + C_{IN}$
IV	Major damage	$H/125 < \Delta < H/50$	$C_R + C_E + C_{DR} + C_{IN} + C_L$
V	Collapse	$\Delta > H/50$	$C_R + C_E + C_{DR} + C_{IN} + C_L + C_{IL}$

where E is the dissipated hysteretic; β_0 is the constant; Q_y is the yielding shear capacity; δ_u is the yielding displacement; x_m is the maximum displacement under the extreme static ice load; x_u is the ultimate displacement of structural collapse (x_u is taken the value of H/50 herein, H is the height of platform). It should be pointed out that the ice-resistant platform is relatively rigid structure and is usually in elastic deformation stage under the static ice load. So the global damage index in Eq. (12) mainly depends on the first item, the structural deformation.

Because there is no available failure loss data for ice-resistant platforms, the classification of structural damage states used in earthquake engineering are employed in this study to describe the respective performance levels. The relationships between structural performances and damage levels under the extreme ice load are shown in Table 1.

3.3 Model of life-cycle cost-effective optimum design

Thus the formulation for the life-cycle cost-effective optimum design of ice-resistant offshore platforms can be represented as follows

$$\begin{aligned} &\mathit{find} \quad X \\ &\min \quad E[C(T,X)] = C_0(X) + \sum_{k=1}^{5} \frac{v_1}{\lambda}(1-e^{-\lambda T}) C_{extremk} P_k \\ &s.t. \quad X_l < X < X^l \end{aligned} \tag{13}$$

where X is the vector of design variables; X_l, X^l are the lower and upper bounds, respectively; $E[C(T,X)]$ is the total expected life-cycle cost; k and m refer to the ordinal numbers of failure modes under the extreme static ice load and the dynamic ice load, respectively; P_k is the probability of failure for the considered kth performance requirement under the extreme ice load.

4. Approximate analysis of the global reliability for the offshore platforms

From the evaluation function of the damage cost in Eq. (3), we need to calculate the failure probability of the failure modes with respect to the global deformation under the extreme static ice load. The global structural reliability analysis based on Pushover analysis attracts more attention, which considers the offshore platform as a global "component" that can resist horizontal and vertical loads, and computes the reliability of the whole capacity. However, in the published papers (Onoufriou and Forbes 2001, Efthymiou *et al.* 1997), a lot of computational efforts are needed because pushover analysis is performed for each sample structure. This paper presents an efficient

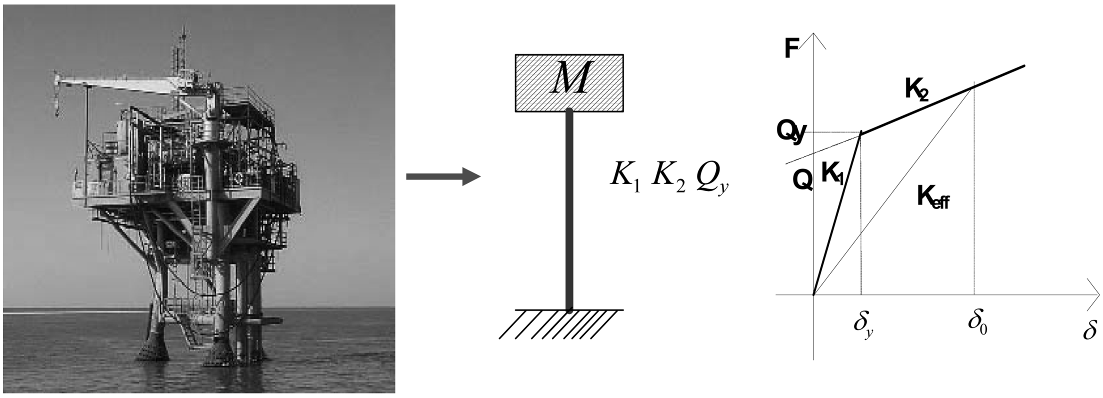

Fig. 1 Global resistance model of offshore platforms

approximate method of the global reliability analysis for the offshore platforms under the extreme ice load.

Firstly, we studied the probability distribution and corresponding statistical parameters of the structural global resistance and the maximum response for some particular type of offshore platform structures (such as jacket platform structures) in Bohai Bay. Considering the randomness of ice load (ice thickness, compression strength, bending strength, etc.) and structure (member geometry size, material modulus, yield strength, etc.), a great deal of samples (such as 1000 or 5000) produced by Monte-Carlo simulation were analyzed.

Thus, the global reliability analysis for the offshore platforms under the extreme static ice load can be solved by using the following approximate algorithm.

(1) Perform the finite element analysis of the offshore platform structure under the static ice load of reference value. Obtain the probability properties (distribution type, mean, coefficient of variation, etc.) of the structural global resistance (see Fig. 1) and the maximum response of the offshore platform according to the above results.

(2) Build the performance function of the global offshore platform structural reliability analysis in terms of resistance and response, whose probability distribution type, mean and C.O.V. are known from step (1). Therefore, the original implicit performance function with respect to the random variable vector **x** and **p**, Eq. (14), can be changed into the linear and explicit performance with respect to random variable u_x and u_p, Eq. (15)

$$f(\mathbf{x},\mathbf{p}) = u_0(\mathbf{x}) - u(\mathbf{x},\mathbf{p}) \tag{14}$$

$$f(u_x, u_p) = u_x - u_p \tag{15}$$

where **x** is the random variable vector concerning structure property (such as member sizes, material property, etc.); **p** is the random variable vector of load effect; $u_0(\mathbf{x})$ is the structural global resistance, random variable; $u(\mathbf{x},\mathbf{p})$ is the maximum response, random variable; u_x and u_p represent the random variables of the structural resistance and maximum response, whose distribution types and parameters are known.

(3) Calculate the reliability of the linear explicit performance function Eq. (15) with general reliability analysis algorithms, such as First-Order Second-Moment Method, etc.

4.1 Random variables statistical properties in the analysis of offshore platform

In the design of ice-resistance platforms in the ice zone, there are many uncertainties related to the member size, elastic modulus of steels, yield stress, dead load, and ice load, etc. The member sizes, elastic modulus of steels, yield stress, dead load follow normal distribution. There are many formulas to calculate the extreme static ice load applied on the platform legs with vertical or conical shape. In the present paper, two typical formulas are used to calculate the extreme static ice load, i.e., API formula (API 1991) or Schwarz formula (Schwarz and Treibsduck 1970) for the vertical structure and Hirayama-Obara formula (Hirayama and Obara 1986) for the conical structure.

(1) API formula

$$F = \alpha\sigma_c Dt \tag{16}$$

where $\alpha = 0.4\sim0.7$, α is taken as 0.4 herein; σ_c is the uni-axis compression strength of ice, $\sigma_c = 2.35 \times 10^6$ Pa; D is the diameter of vertical leg; t is the ice thickness.

(2) Schwarz formula

$$F = 500 \times D^{0.5} \times t^{1.1} \times \sigma_c \tag{17}$$

where all parameters are the same to those in the API formula.

(3) Hirayama-Obara formula

$$F = B \times \sigma_f \times \left(\frac{D'}{l_c}\right)^{0.34} \times t^2 \tag{18}$$

where $B = 3.7$; σ_f is the bending strength of ice, $\sigma_f = 7.0 \times 10^5$ Pa; D' is the diameter of the conical leg; l_c is the characteristic length of ice, $l_c = (Et^3/12\rho_w g)^{0.25}$; E is the ice elastic modulus, $E = 5 \times 10^8$ Pa; g is the gravity acceleration, $g = 9.8$ m/s^2; ρ_w is the density of sea water, $\rho_w = 1.0 \times 10^3$ kg/m^3.

The parameters of the random variables are summarized in Table 2.

Table 2 Random variables statistical properties (Li 2003, Ji *et al.* 2002)

Random variables	Probability distribution	Ratio of mean to standard value	Coefficient of variation
Dead Load(top mass)	Normal	1.060	0.070
Geometry Dimensions	Normal	1.000	0.020
Elastic Modulus of Steel	Normal	1.080	0.080
Yield stress of steel	Log Normal	1.210	0.150
Extreme Ice Thickness	Log Normal	1.104	0.247
Compression Yield Stress of Ice	Normal	0.961	0.115
Bending Yield Stress of Ice	Normal	0.757	0.159
Diameter of leg	Normal	1.000	0.02

4.2 The probability statistical properties of offshore platform structural global resistance

In this work, three offshore jacket platforms in Bohai Bay were studied as examples, JZ202MSW (three-leg platform), MUQ (four-leg platform), and NW (one-leg platform). 1000 samples of each practical platform are generated based on the probability distributions of the concerned random variables, and Pushover analysis was performed to each example. Then statistical results of the structural global resistance parameters can be obtained, including elastic stiffness $\mathbf{K}_1$, post-yield stiffness $\mathbf{K}_2$, yield roof displacement δ_y, and system yield force $\mathbf{Q}_y$, as shown in Fig. 1.

The static Pushover analysis was presented and developed over the past twenty years by Saiidi and Sozen (1981), Fajfar and Fischinger (1988), which has undergone a lot of developments these years, particularly in the area of performance-based seismic design. The essence of Pushover analysis is static elastic- plastic analysis in combination with response spectrum. In the pushover analysis of offshore structure, a monotonously increasing load is applied at the water level of the structure until it is pushed to a given target displacement, by which the non-linear behavior of the structure can be obtained. The basic steps of Pushover analysis in this work are:

(1) Establish the finite element model of the sample structure.

(2) Select a suitable load mode, which is applied at the water level of the jacket platform.

(3) Perform elastic- plastic analysis using ANSYS. Increase load monotonously step by step until the weakest member yields. Then modify the stiffness matrix of the yield member.

(4) Repeat step 3 until the roof displacement of the structure reaches the target value, which is taken as H/100 in this study (H is the height of the jacket platform).

(5) Obtain the relationship curve between the roof displacement and base shear in different stages. Using the equivalent energy method or direct curve-fitting technique, convert the original pushover curve into the bilinear one.

Based on the results of Pushover analysis for 1000 sample platforms, the critical value Dn ($\alpha = 0.05$, $Dn = 0.0428$) of k-s test under the hypothesis of normal distribution and the statistical parameters of the structural global resistance are shown in Table 3 and Table 4 respectively. And the following observations can be obtained:

Table 3 Statistic parameters of the platform structural global resistance

Platform	Elastic stiffness		Post-yield stiffness		Yield roof displacement		System yield force	
	Mean/ Reference	C.O.V.	Mean/ Reference	C.O.V.	Mean/ Reference	C.O.V.	Mean/ Reference	C.O.V.
MUQ	1.07665	0.0884	1.0082	0.0343	0.9377	0.0847	1.0026	0.01606
MSW	1.11619	0.0859	1.0328	0.0721	0.9093	0.0840	1.0079	0.02424
NW	1.07786	0.0827	1.0610	0.0661	0.9371	0.0792	1.0040	0.01849
average	1.09023	0.0857	1.0340	0.0575	0.9280	0.0826	1.0048	0.01960

Table 4 The critical value Dn of k-s test under normal distribution hypothesis

Platform	Elastic stiffness	Post-yield stiffness	Yield roof displacement	System yield force
MUQ	0.0222	0.0189	0.0303	0.0150
MSW	0.0211	0.0233	0.0253	0.0375
NW	0.0198	0.0259	0.0419	0.0174

(1) Probability distribution: The structural global resistance parameters (bilinear model, as shown in Fig. 1), including the elastic stiffness $\mathbf{K}_1$, post-yield stiffness $\mathbf{K}_2$, yield roof displacement δ_y, and system yield force $\mathbf{Q}_y$, follow normal distribution, as shown in Table 4.

(2) Statistical parameters (Table 3): The Ratio of the mean to the reference value of the global resistance parameters is almost same, with the maximum difference of 5.0% (post-yield stiffness). The coefficients of variation (C.O.V.) of elastic stiffness and yield roof displacement are consistent. However the coefficients of variation of system yield force and post-yield stiffness are quite different with the difference of 33.83% and 52.4%, respectively.

4.3 Statistical properties of the maximum response induced by extreme static ice load

Using nonlinear finite element analysis, the maximum response of 1000 samples of JZ20-2 MSW, MUQ and NM jacket platform under the extreme static ice load were determined respectively. The statistical parameters of the maximum roof displacement and the critical value *Dn* ($\alpha = 0.05$, $Dn = 0.0428$) of k-S test under the hypothesis of lognormal distribution are shown in Table 5. The results show:

(1) The maximum roof displacement of jacket platforms under the extreme ice load obeys lognormal distribution.

(2) The ratios of mean to standard value of the maximum roof displacement are almost the same for each case (without and with conical device), respectively, and the maximum difference is 3.0%; So is the coefficients of variation, with the maximum difference is 2.4%. The averages of the ratios of mean to standard value of the maximum roof displacement using three different ice load formulas are 0.98653, 0.99622, and 0.85905 respectively; the averages of the coefficients of variation are 0.28472, 0.31341, and 0.47922 respectively.

Table 5 Statistic parameters of the maximum roof displacement and the critical value *Dn* of k-s test under lognormal distribution hypothesis

Ice load formula	Platform type	Standard value	Mean	Ratio of mean to standard value	Coefficient of variation	*Dn*
API formula	MSW	0.02001	0.02010	1.00450	0.28753	0.0210
	MUQ	0.00231	0.00229	0.99134	0.29188	0.0221
	NW	0.01130	0.01101	0.97434	0.28582	0.0205
Schwarz formula	MSW	0.03101	0.03115	1.00452	0.30941	0.0214
	MUQ	0.00308	0.00307	0.99675	0.31380	0.0206
	NW	0.01019	0.01008	0.98921	0.31509	0.0330
Cone structure formula	MSW	0.00958	0.00843	0.87996	0.47661	0.0209
	MUQ	0.00082	0.00072	0.87805	0.48853	0.0156
	NW	0.00209	0.00182	0.87081	0.47953	0.0147

5. Application to the design of a typical offshore platform

To demonstrate the life-cycle cost-effective design of ice-resistant platforms, an illustrative example of a typical platform in Bohai Bay is discussed herein. For the offshore platforms, the mass mainly depends on the facilities on the platform. So the dynamic characteristics, structural responses under the extreme ice load are mainly determined by the structural global resistance. Furthermore the structural global resistance is closely related to the initial cost. In the optimal design, the structural global resistance (stiffness) is taken as the design variable, and JZ20-2MSW platform is selected for study, shown in Fig. 1. The platform is a jacket structure of three legs with 4m-diameter ice-breaking cones. The total upper mass is 200t, and the design depth of water is 16.5m. It is assumed in Eq. (13), that the occurrence rate of extreme static ice load is 0.2/year, the service life of the platform is 20 years, and the annual discount rate is 6%.

5.1 Initial cost estimation

Initial cost C_0 in Eq. (13) is expressed as an approximate linear function of the structural global resistance, and is the sum of the material cost C_m and the labor cost C_l (assume 60% of the material cost) $y = 22.987x + 75.869$, where y is the weight of steel (ton) and x is the structural initial stiffness (10^7 N/m).

5.2 Damage cost estimation

To calculate the expected failure cost some parameters in Eqs. (6)~(11) should be given based on the actual investigation. Since the relevant data in Bohai Bay is not available, the data for the Mexican platforms are used, as shown in Table 6.

The evaluation of expected damage costs utilizing Eq. (3) requires the reliability analysis for all failure modes considered in the life-cycle cost model. The failure probabilities based on the approximate global reliability analysis are shown in Fig. 2.

Table 6 Associated parameters of damage costs

Parameter	R_c	D_R	C_E	C_P	C_{1I}	N_I	C_{1L}	N_D	C_{LC}	C'_{LC}	C_{repair}
c_{fi}/c_0	1	0.6	3	100	0.0005	10	0.004	10	3000	300	0.5

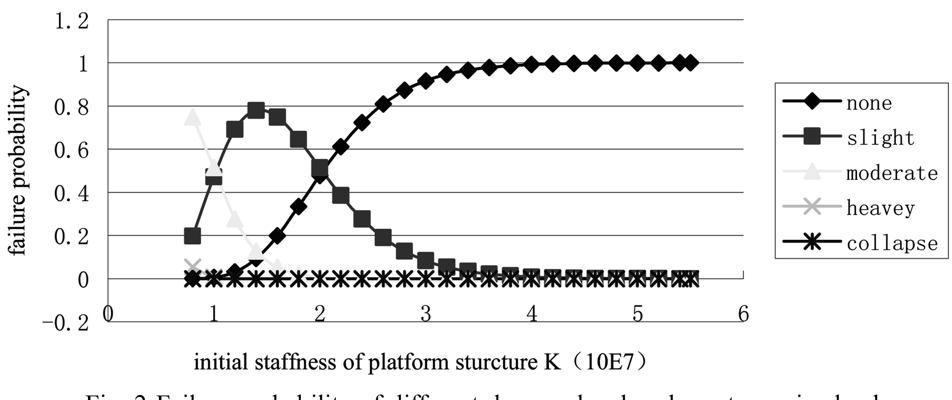

Fig. 2 Failure probability of different damage level under extreme ice load

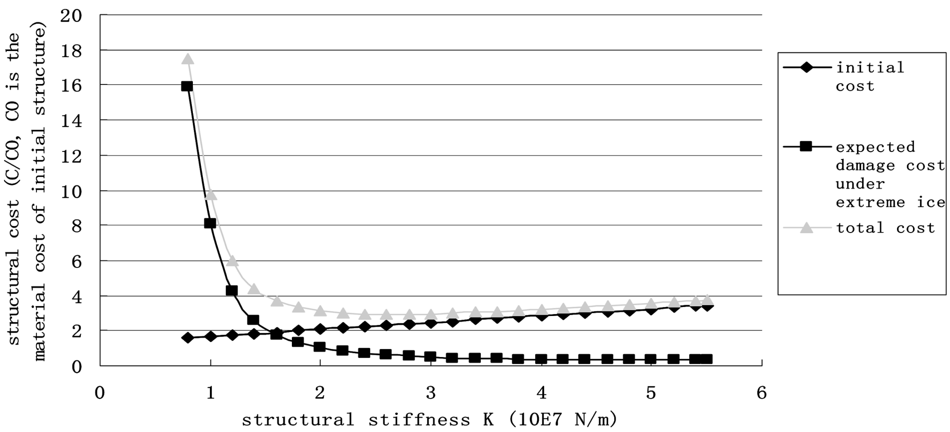

Fig. 3 Costs versus structural global stiffness in the service life

Table 7 Comparison of life-cycle optimum design and conventional design

	Conventional design	Life-cycle optimum design
Global stiffness (10^7 N/m)	5.36	2.60
Initial cost (C_0)	3.4000	2.3024
Cextreme (C_0)	0.3228	0.6114
Total cost (C_0)	3.7228	2.9138

5.3 Expected life-cycle cost functions

Within the given structure stiffness, the plots of the resulting life-cycle cost function, including initial cost, expected damage cost and total cost are shown in Fig. 3. The life-cycle optimum results are compared with the conventional static design (the real design) and the dynamic deterministic optimum design, shown in Table 7.

Some observations can be obtained from Fig. 3 and Table 7:

(1) The trade-off between the initial cost and the expected cost of damage is the pursued in the optimal design, which corresponds to the global design stiffness $K = 2.6 \times 10^7$ N/m. The global deformation under the extreme ice load and corresponding damage costs go down as the structural global stiffness increases. However, the initial cost will significantly increase.

(2) From Table 7, we can compare the effect of the initial cost on the total expected life-cycle cost by various design methods. It is found that the initial cost and total cost of life-cycle optimum design are decreased by 32.28% and 21.73% compared to that of the conventional design. The conventional static design is conservative in that the initial cost is very high. Thus, the life-cycle cost-effective design, considering both the initial cost and the expected damage costs under the extreme ice load, is more rational.

6. Conclusions

In the marginal oil field located in the ice zone, both the ice-resistant capacity and the economical investment are two design aims of great concern for the offshore platforms. The life-cycle cost-effective design is a promising design approach, which has undergone a lot of developments in many engineering areas. Accordingly, this paper addressed the optimum design to minimize the expected life-cycle cost for ice-resistant platforms based on cost-effectiveness criterion. A practical life-cycle cost formulation for ice-resistant jacket platforms is proposed comprising the initial cost and the damage cost, repair cost, death and injury loss, indirect socio-economic loss as well as discounting cost over time. Multiple performance demands of the structure, facilities and crew members under the extreme ice load are treated and the corresponding evaluation functions are formulated. An efficient approximate method of the global reliability analysis for the offshore platforms is proposed. Finally, the life-cycle cost-effective optimum design formula is applied to a real jacket offshore platform, and the results show that the life-cycle cost-effective design may lead to more rational, economical and safer design compared with conventional design.

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