Structural Performance Analysis of Simple Offshore Platforms under Ice-Vibrations in Bohai Sea

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Abstract: In China, the oil and natural gas resources of Bohai Sea are mainly marginal oil fields. It is necessary to build both ice-resistant and economical offshore platforms. So, several simple offshore oil platforms with a jacket sub-structure or with a single pillar have been deployed. There are very good economic benefits in the manufacture, installation, removal, and other aspects. These platforms were primarily designed to withstand extreme static ice forces. However, sea ice motion can induce significant vibrations for the platforms in the region. The structural ice-resistant performances have not been well developed. In this paper, combined with the field monitored data of some simple platforms in Bohai Sea, ice-induced vibrations are analyzed. The results show that even though these structures may effectively resist extreme static ice forces, the ice-induced acceleration is more significant. Then, spectral-based method is provided to analyze the fatigue life of a real simple platform. Lastly, the ice-resistant strategy is presented, which provides a basis for the design of these platforms in ice zone.

Keywords: Ice-induced vibration, ice-resistant structure, simple offshore platform, Bohai Sea.

1. INTRODUCTION

The cost of construction for the offshore platforms in the oil field development occupies an important proportion to the total investment of the oil production in Bohai Sea. The Gravity Based Structure and piled jacket platform are widely used currently. But the two kinds of platforms are so expensive that they account for large proportion of the total investment. Taking the steel jacket structure for example , the steel of the piles is as much as the jacket structures'. While the cost of installing one platform at sea is nearly half of the total cost. Nowadays , the bucket foundation platform is known as a new style foundation of platform, which is paid more attention for it's peculiarity such as low weight, easy installation and repeat use, and other aspects. Therefore , the bucket foundation platform is very significant for the oil field development in the marginal oil fields.

The bucket foundation platforms have been widely used in Denmark and Norway. And a large bucket foundation jacket platform is achieved [1]. There were six simple bucket foundations platforms, which have been used for some auxiliary function , such as shooting practice for navy, anchoring for mooring buoys, and so on, designed and successfully installed from 1996 to 2000 in China. At present, the research of the bucket foundation platform is mainly concerted on the foundations, including suction penetration and the installing stability of the bucket foundation [2-5]. For the marginal oil field in Bohai Sea, ice load is the control force for the ice-resistant structures [6]. And the interaction between the ice-induced vibration and the bucket foundation platform has not been recognized clearly, which is one of the reasons that restrict the development of the bucket foundations of offshore platform in the ice zone. Therefore, the application of these platforms in Bohai only accomplished some auxiliary function. In this paper, combined with the field monitored data of some bucket foundation platforms in Bohai bay, ice-induced vibrations are analyzed. It indicates that the ice-induced acceleration is so serious, and is more significant than the jacket platforms. Then spectral-based method is provided to analyze the fatigue life of a real bucket foundation platform, according to the results, the fatigue life of the key joint can meet the requirement. Finally, the ice-resistant strategy is presented, which provides a basis for the design of these platforms in ice zone.

2. FIELD MONITORING TEST OF THE BUCKET FOUNDATION PLATFORM WITH A SINGLE PILLAR

In order to analyze the dynamics response of the bucket foundation platform under the time-varying ice forces, extensive monitoring has been conducted on some of the Bohai Sea platforms. The observation methods used are: accelerometers installed at different levels measure the structural response in different directions, load panels installed on the legs measure the time-varying ice forces, video cameras observe the ice failure mode and are used to estimate ice thickness, and a marine radar, meteorological station, and current meter are used to track environmental conditions and monitor ice movement. Figure **1** below

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E-ISSN: 2409-787X/18

shows the test set-up on the bucket foundation platforms with a single pillar. From this image, we get quantity of data including the ice force and the ice-induced vibration response. Therefore, the anti-ice performance of the bucket foundation platform with a single pillar will be studied.

2.1. Dynamic Ice Force Based on Field Data

The time-varying ice forces can be obtained from the monitoring ice load panels. When ice interact with a vertical structure, many different failure modes such as bending, shear, buckling and crushing etc., could take place depending on the contacting conditions. And the crushing failure is the most common case. For vertical structures, three vibration modes, quasi-static force induced vibrations, steady-state vibrations and random vibrations may appear during ice crushing failure with the ice speed changing from low to fast. Figure **2** shows a typical vertical structure's time-varying force curve.

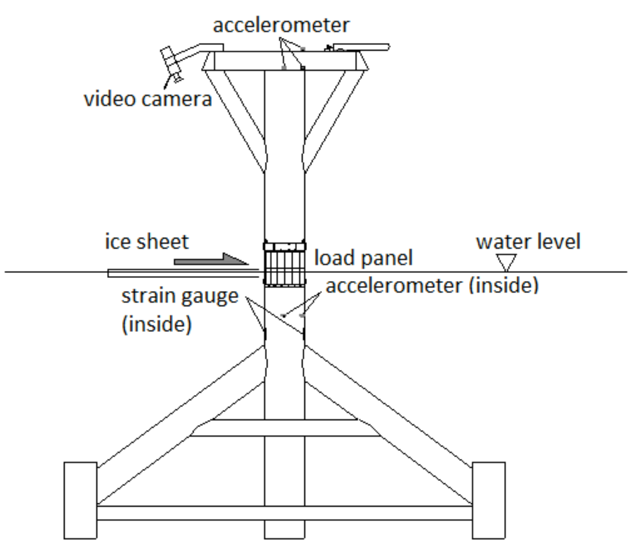

Figure 1: Monitoring set-up for the bucket foundation platforms with a single pillar.

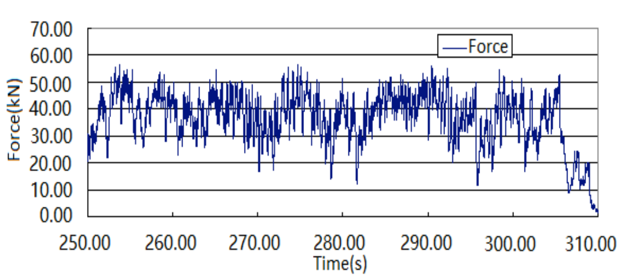

Figure 2: The typical time-varying force curve.

2.2. Dynamic Ice-Induced Vibration Response Based on Field Data

According above, three kinds of vibration modes could be induced depending on the ice speed. The steady-state vibration is the most severe condition [7]. The steady-state vibration is a self excitation mode. The amplitudes of response are very large and the frequency remains nearly constant. This vibration process may last for several minutes and the amplitude stays invariant, which is very harmful to the structure [8-10]. And the crew feels uncomfortable. According to the field data, the acceleration response of the bucket foundation platforms with a single pillar is much more serious than the traditional jacket platforms nearby. The comparison of the maximal value every day between the two kinds of platforms is shown in Figure **3**. It's obvious that the bucket foundations have been found much stronger ice-induced vibration phenomenon. The reasons are that the bucket foundation structure has smaller upper mass and the height of the structure is lower. So its stiffness is much larger, the damping is smaller, and its natural frequency is larger than the typical jacket ones. The frequency of the vibration response based on field data is shown in Figure **4**.

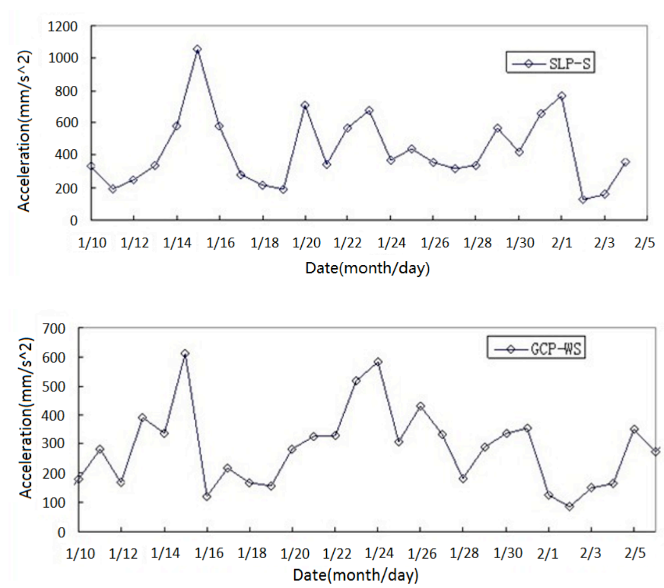

Figure 3: The comparison of the vibration response between the bucket foundations and the jacket structures.

3. THE FATIGUE ANALYSIS OF A TYPICAL BUCKET FOUNDATION PLATFORM WITH A SINGLE PILLAR

It is discovered that the bucket Foundations ice-induced vibration is so serious based on the field data.

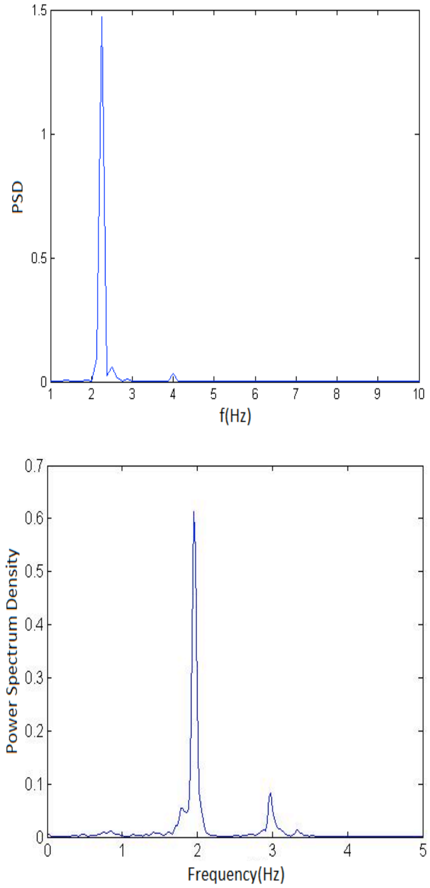

Figure 4: The comparison of the frequency of the vibration response between the bucket foundations and the jacket structures (the bucket foundation: 2.3Hz; the jacket structure: 1.90Hz).

The fatigue failure of pipelines is the main failure mode under the dynamic ice force [11]. Taking JZ9-3WHPE platform for example (shown in Figure **5a**), the fatigue damage of this platform is analyzed based on the field data and ANSYS software. The method of safety life is chosen to estimate ice-induced fatigue life in this paper, which is suitable to apply to the offshore structures [12]. The method of safe life is mainly based on Miner's linear cumulative fatigue hypothesis (1) and S-N curve data (2).

$$D = \sum n_i / N_i = 1 \tag{1}$$

$$N = 2 \times 10^6 \left(\frac{\Delta\sigma}{\Delta\sigma_{ref}} \right)^{-m} \tag{2}$$

Where, the cycles to failure N at each of the expected stress levels based on S-N curve data from API 2A standards for offshore platforms (API 1988). N is the number of cycles to failure, σ_{ref} is taken to be 100 N/mm^2, m is taken to be 4.38, and σ is the stress level in N/mm^2 for which the number of cycles to failure is desired.

Spectral methods to estimate ice-induced fatigue life are as follows:

1. **Building the structural element model:** It's needed to determine the structure's mode and frequency in terms of the structure's geometric and physical properties. Geometric properties include the scale of the structure, the number of the nodes, and the cross-sectional area, etc. Physical properties include the structure's stiffness, mass and damping. The element model of JZ9-3WHPE is shown in Figure **5b**.

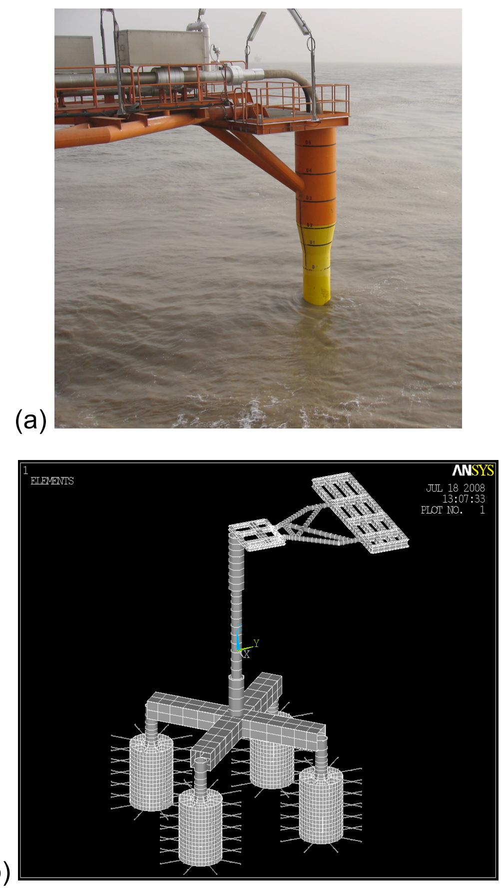

Figure 5: Jz9-3WHPE platform and its finite element model.

2. Building the ice fatigue environmental model: Long-time ice condition data is the base of building the model of fatigue ice environment. Ice fatigue environmental parameters should include ice thickness, ice velocity, ice flexural strength, ice period and ice flow direction. Ji accumulated integrated several years' ice condition data in

Table 1: Probabilities of the Different Ice Cases

		Ice thickness (cm)					
Ice velocity (m/s)		0-6	6-12	12-18	18-24	24-30	Sum = 0.991
	0-10	0.0260	0.0250	0.0058	0.0013	0.0003	
	10-30	0.1610	0.1530	0.0360	0.0083	0.0021	
	30-50	0.1600	0.1520	0.0360	0.0082	0.0021	
	50-70	0.0750	0.0720	0.0170	0.0039	0.0010	
	70-90	0.0200	0.0190	0.0044	0.0010	0.0003	

Bohai Sea, which compose the foundation of building the ice fatigue environmental model [13]. The statistical distributions of ice period and ice thickness are summed up and appear in Table **1** below.

3. **Building the ice force spectrum:** Based on field data, Tuomo Kärnä and Yu [14] analyzed the ice load spectrum acting on the vertical platform, which can be applied as:

$$S(f) = \frac{7.2\sigma^2}{1 + 10.4 \times 7.2^{1.5} f^2} \quad (3)$$

Where, σ is the variance of Ice force, can be calculated as follows:

$$\sigma = \frac{I_F}{1 + mI_F} F^p \quad (4)$$

where I_F is the strength of dynamic ice load , considered to be 0.4; $m = 3$, F^p is static ice load of vertical platform, which can be determined by $F = \alpha\sigma_c Dt$. Where σ is influence coefficient as 0.4-0.7; θ_c is uniaxial compressive strength of ice as 2.1 MPa; D is the diameter of the pile; *t* is the ice thickness.

4. **The dynamic analysis:** Firstly, the ice force spectrum is put into the finite element model. Then the stress spectrums under all kinds of conditions are achieved by series of calculation. And then the variances of the stress are got. Then the stress cycle curve according to Rayleigh distribution is established. The probability density function of the peak stress can be written as follows:

$$P(\sigma) = \frac{\sigma}{\sigma_S^2} \exp(-\frac{\sigma^2}{2\sigma_S^2}) \quad (5)$$

Where *P*(*σ*) - The stress peak probability density ; θ_s - The standard deviation of stress. The stress standard deviation of the tube hot spot is as shown in Table **2**.

Table 2: The Stress Deviation of the Hot Spot under all Kinds of Conditions (MPa)

		Ice Thickness (cm)				
Ice Velocity (m/s)		0-6	6-12	12-18	18-24	24-30
	0-10	2.18	6.64	12.11	14.67	18.94
	10-30	2.66	7.67	14.83	23.72	23.80
	30-50	3.17	8.48	15.82	25.13	30.56
	50-70	3.64	9.34	16.90	26.35	37.60
	70-90	4.01	10.22	18.07	27.70	39.10

5. **Estimate the number of stress cycles under each ice condition:** The number of stress cycle of the structure under each ice condition, can be expressed as:

$$n_j = P_{lcj} \cdot d \cdot 24 \cdot 3600 \cdot f \quad (6)$$

Where : *d* - ice period, days, (42 days); P_{Lcj} - the probabilities of the *j*-ice condition

f - the natural frequency of the structure, Hz, (6.19HZ);

So the stress distribution will be integrated. Then the cyclic number of the amplitude changing stress $\mathrm{B}\theta_i$ under the ice condition *j* is calculated using Eq. (7) and the results are listed in Table **3**.

$$n_{ji} = n_j \cdot P(\Delta\sigma_i) \quad (7)$$

6. **Estimate the fatigue Life:** cumulative damage can be obtained with miner theory, $D = \sum_{i=1}^{m} D_i = 1$, the fatigue damage under each condition is shown in Table **3**. The fatigue life *T* = 1 / *D* = 303 years.

Table 3: The Fatigue Damage D_i of the Hot Spot under Kinds of Conditions

		Ice Thickness (cm)				
Ice Velocity (m/s)		0-6	6-12	12-18	18-24	24-30
	0-10	3.70E-08	4.69E-06	1.52E-05	8.11E-06	6.45E-06
	10-30	5.53E-07	5.39E-05	2.28E-04	4.10E-04	1.08E-04
	30-50	1.17E-06	8.30E-05	3.03E-04	5.25E-04	3.22E-04
	50-70	1.01E-06	6.02E-05	1.91E-04	3.03E-04	3.74E-04
	70-90	4.14E-07	2.36E-05	6.61E-05	9.88E-05	1.16E-04

According to the corresponding API specification, the corresponding stress concentration factor is taken 2-3. So the result indicates that the fatigue life of Jz9-3WHPE platform satisfies the design requirement.

4. SUGGESTIONS TO RESIST THE ICE-INDUCED VIBRATION

Based on the field data and the numerical simulation, it's indicated that the acceleration induced by the dynamic ice force is so serious, which may endanger the pipelines on the platform. However, Fatigue failure induced by ice vibration of this kind of structure is not the key issue because there are few tube nodes compared with the jacket platforms. Here are some suggestions to resist the ice-induced vibration for the simple ice-resistant structures:

(1) Adding ice-breaking cone: The ice force is mainly determined by the failure mode. The crushing failure is the main failure mode when the ice interacts with the vertical structure. On the other hand, the bending failure is the main failure as the ice acting on the conical ones. The ice load and ice-induced vibration are reduced because the bending intensity is much lower than crushing intensity. At present, the ice-breaking cones have been installed on many vertical structures to mitigate the ice induced vertical structure steady state vibration in Bohai Sea. So, the bucket foundation platform with a single pillar should be added the ice-breaking cone.

(2) Dynamic absorption of vibration: it is practical as the additional control system which does not change the dynamical attribution of the platforms themselves. It is usual that the equipment of dynamical absorption of vibration is installed on the top of the platform, i.e. the maximum displacement in the first modal.

(3) Isolation arrangement: it is to limit the vibration to be transferred to the structure by isolating structure from vibration source. It reduces obviously the acceleration by increasing the self-oscillation period. The top structure can be assumed as rigid body because the deformation of the structure above the vibration insulation is negligible when the main deformation takes place on the vibration insulation.

5. CONCLUSION

At present, the application of the bucket foundation in the ice region is not very mature and it is only used as assistant platform in Bohai Sea. Because the interaction between the dynamic ice force and the bucket foundation structure haven't been recognized clearly. In this paper, the bucket foundation platform is studied based on the years' field data. The results indicate that the acceleration induced by the dynamic ice force is so serious, which may make the upper pipe line failure. However, Fatigue failure of this kind of structure is not very serious. In order to make the bucket foundation platform apply in the ice region, the suggestion to resist the ice-induced vibration is performed. The method of adding the ice-breaking cone should be adopted for the existing platforms. Taking the Jz9-3WHPE bucket foundation with a single pillar for example, the ice-induced vibration is reduced evidently after the ice-breaking cones added on the bucket foundation in 2008.

6. ACKNOWLEDGEMENT

The support of the National Natural Science Foundation of China (51679033, 51309046), State's Key Project of Research and Development Plan (2016YFC0303400), the Special items of national marine public welfare industry (201505019) are much appreciated.

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Received on 20-07-2018 Accepted on 10-09-2018 Published on 17-11-2018

DOI: http://dx.doi.org/10.15377/2409-787X.2018.05.5