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Study on the structural monitoring and early warning conditions of aging jacket platforms

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ABSTRACT

In this paper, the structural monitoring methods and early warning conditions were proposed based on the characteristics of the aging jacket offshore platforms, including the monitoring and early warning condition of the displacement, the bearing loads of pile end and the platform subsidence. On the basis of pushover analysis, the curves of base shear force versus deck displacement were drawn. Furthermore, the anticipated risks were classified into three levels due to different deformations in the collapse process; the three level early warning conditions were established. A method of the monitoring of the bearing loads of pile end was put forward, with the calculating of the load transmission function. The early warning condition that the bearing loads of pile end should not exceed half of the ultimate pile capacity was provided based on API RP 2A-WSD. The long-term monitoring method of the platform subsidence was presented based on the calculating of the difference of elevation between any two pile tops. The early warning conditions considering the stress and tilt requirements were established. The monitoring method has been applied to a jacket offshore platform on the South China Sea, and the result illustrates the feasibility of this method.

1. Introduction

Many jacket offshore platforms in China have been approaching or exceeded their original design lives, and during their service time, they have been suffering the averages such as corrosion, subsidence, scouring, fatigue and accidental damages. Besides, in order to maximize the economic benefit, renovation projects, including additional conductors and topsides modification, are universally seen in most of offshore platforms. The real-time monitoring of the offshore platform is in urgent need to judge whether the offshore platforms are available to operate or not, and the early warning conditions are required to make contingency plans to ensure personnel security.

Mangal et al. (2001) adopted vibration responses due to impulse and relaxation for structural monitoring of offshore platforms. Nichols (2003) established a new method for monitoring the integrity of offshore structures using ambient excitation. Kianian et al. (2013) presented a damage detection method using frequency domain selective measurements and the proposed method was carried out on a two-dimensional jacket platform on the basis of numerical study. Xu et al. (2013) proposed sensitivity diagnose method based on the fact that some members of jacket platform are very sensitive to the damage of the structure. Liu et al. (2012) put forward a damage diagnosis method based on genetic algorithm, using an improved objective function according to the noise measurement and the characteristics of modal identification for offshore platform. Liu et al. (2011) detected the structural damages with different cases using genetic algorithm and mode strain energy method based on model tests. Ou et al. (2001) developed a real time safety monitoring system for offshore platform using corrected real time calculation model based on the environment monitoring. Wang et al. (2010) and Xu et al. (2008) proposed the long-term monitoring method of deck load and the variety of the upper load with fiber brag grating sensors. Wang et al. (2012) inspected the pile foundation bearing capacity of an offshore platform in Bohai Bay and had taken a one-year settlement monitoring for it. Setan and Othman (2006) monitored the subsidence of offshore platform using permanent GPS stations. But the accuracy of the method is relatively low, while the cost is relatively high. Wang et al. (2011) proposed a three-level subsidence monitoring method based on the soil compress characters and the subsidence harmful degrees, but the computing method especially for the settlement has not been

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given. Up to now, a perfect monitoring method for offshore platforms has not been established, and neither has the uniform standard for the warning conditions correspondingly.

In the monitoring process, how to gain the bearing loads of pile end, as well as the subsidence? And what early warning conditions shall be chosen to evaluate the service state of the platform after having gained the relative monitoring data? The solutions of these questions are crucial to the security of aging offshore platform. In order to solve these problems, a monitoring system for the integrity of offshore platforms is developed, including the monitoring of the displacements, the bearing loads of pile end and the settlements and the early warning mechanism correspondingly. The application performed very well on a jacket platform on the South China Sea.

2. Displacement monitoring and warning condition

2.1. *Ultimate strength analysis*

Ultimate strength analysis was performed to research the relationship between the deck displacements and the corresponding deformations in the structure. Accordingly, the deck displacements were monitored to detect the deformations of the offshore platform, and simultaneously different level warning conditions would be issued based on different potential risk of the deformations such as member initial yielding, pile initial yielding, pile pull-out or pile punch-through, and last collapse.

Pushover analysis (Zhu et al., 2014) is a common method to analyze the ultimate strength of the offshore platform. This method involves a single static load pattern corresponding to a particular choice of wave, current and wind. This load applied to the structure is typically increased monotonically up until the structure as a whole collapses or is pushed over. For each step, the nonlinear events such as joint flexibility and member plasticity will be concerned. The pile–soil interaction was also been considered in this paper.

The twelve directions shown in Fig. 1 were typical used for the pushover analysis, including broadside directions (90 and 270 degree), longitudinal directions (0 and 180 degree), and diagonal directions (35, 49, 131, 145, 215, 229, 311 and 325 degree). These twelve attack directions were chosen for their storm severity. The pile–soil interaction was taken into account based on T–Z, P–Y, and Q–Z data, and the pile elements were included as plastic members.

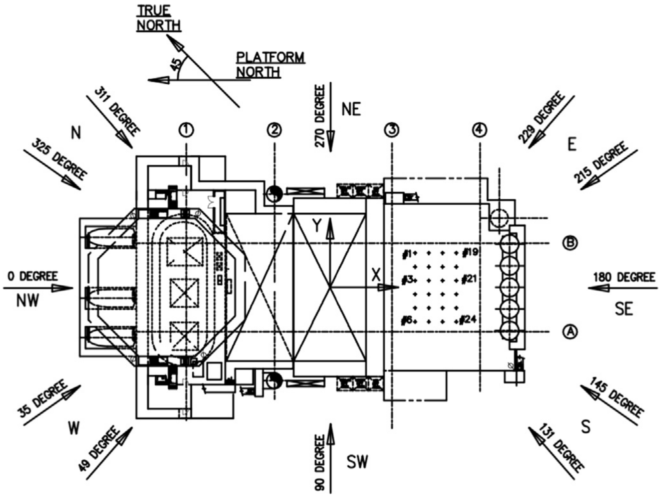

Fig. 1. Directions of pushover analysis.

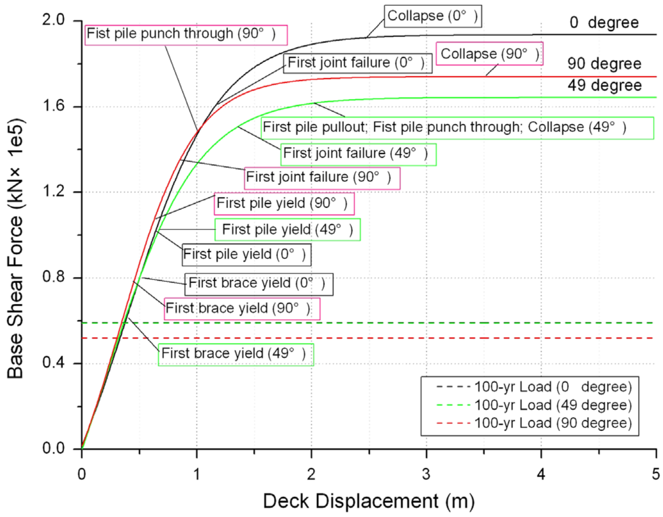

Fig. 2. Base shear force versus deck displacement.

2.2. *Pushover analysis results*

Fig. 2 shows the base shear forces plotted against the deck displacements for the three typical direction pushovers of 0, 49 and 90 degree. From the figure, the following observations can be made

In 0 degree direction: as the deck displacement value increases up to 0.527 m, the first brace starts yielding; and up to 0.673 m, the first pile begins yielding; and up to 1.172 m, the first joint failure occurs; and up to 2.511 m, the structure collapses.

In 49 degree direction: as the deck displacement value increases up to 0.401 m, the first brace starts yielding; and up to 0.664 m, the first pile begins yielding; and up to 1.365 m, the first joint failure occurs; and up to 2.020 m, the structure collapses.

In 90 degree direction: as the deck displacement value increases up to 0.445 m, the first brace starts yielding; and up to 0.633 m, the first pile begins yielding; and up to 0.850 m, the first joint failure occurs; and up to 3.491 m, the structure collapses.

2.3. *Early warning conditions*

According to the pushover analysis results aforementioned, as the load increases monotonically, the deck displacement increases correspondingly and the corresponding deformation occurs. The platform conditions of different deck displacements would be classified based on the fact that different deformations implicate different levels of risk or consequence. The first brace initial yield might result in local damage and weaken the local strength of the structure, which is defined as low class risk, and simultaneously, the early warning defined as Blue Pre-Warning would be issued. Similarly, the first pile initial yield is defined as middle class risk and corresponding Orange Pre-Warning would be issued, and the first joint failure is defined as high class risk and corresponding Red Pre-Warning would be issued, as listed in Table 1.

On the basis of the analysis stated above, the three-level warning conditions corresponding to the deck displacements reflecting the risk classes are established, as shown in Fig. 3. The Red Pre-Warning condition is conserved, since the ratio of the warning base shear force to the capacity (RWC) is ranged from 0.677(for 270 degree, broadside direction) to 0.893(for 35 degree, diagonal direction), quite lower than 1.0.

Table 1
Classification of the warning conditions.

Deformation	Risk level	Consequence	Warning condition classification	RWC
First brace initial yield	Low class risk	Local damage; local strength reduced;	Blue Pre-Warning	0.357~0.5
First pile initial yield	Middle class risk	Pull out; Punch through;	Orange Pre-Warning	0.541~0.679
First joint failure	High class risk	Widespread damage; Collapse;	Red Pre-Warning	0.677~0.893

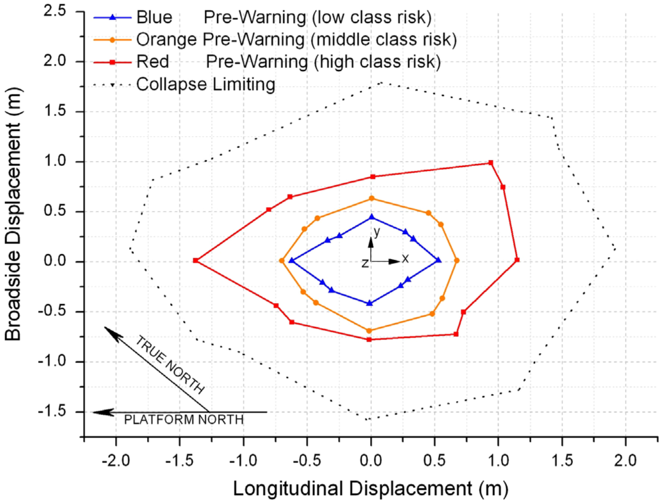

Fig. 3. Displacement warning conditions.

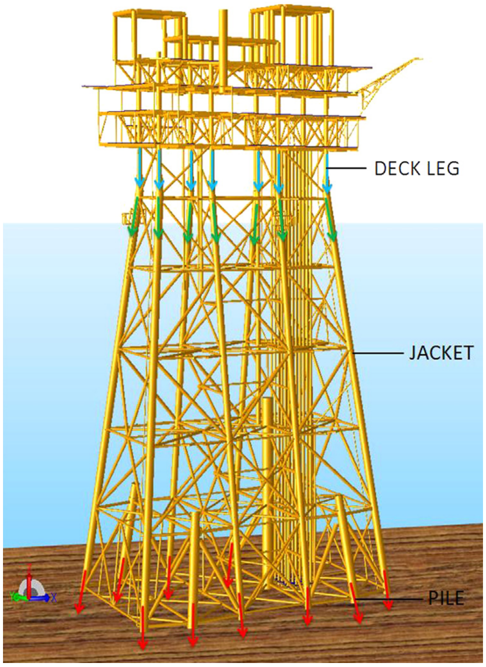

Fig. 4. Transmission of the upper load.

3. Bearing loads of pile end monitoring and warning conditions

3.1. Bearing loads of pile end monitoring

The jacket type offshore platform comprises of a topside fixed on an eight legged steel jacket supported by twelve piles (including four skirt piles), as shown in Fig. 4. The topside load is distributed on the eight deck legs and transferred to twelve piles through the steel jacket structure. Therefore, the whole load concentrates on the piles sustained by the foundation. The transmission of the upper load is illustrated in Fig. 4.

The bearing loads of pile end are made up of the initial pile–head loads, the additional pile–head loads and the weights of the part of piles under mud line. Moreover, the initial pile–head loads could be calculated using FEM considering the ocean environmental loads, meanwhile the additional pile–head loads could be produced from the additional upper loads, which could be gained by real-time monitoring, and the load transmission function. In light of this, a method of monitoring the bearing loads of pile end for the jacket offshore platform is introduced as below.

The jacket structure is idealized and assumed as a linear system before the structure steps into inelastic stage. The additional upper loads and the load transmission function are expressed as ΔF (gained by monitoring) and C (will be analyzed below) respectively, hence the additional pile–head loads may be calculated by the equation:

$$\Delta P = C \times \Delta F \tag{1}$$

The initial pile–head loads are P_0 (calculated using FEM), and the weights of the part of the piles under mud line are W, then the bearing loads of pile end may be calculated by the equation:

$$P = C \times \Delta F + P_0 + W \tag{2}$$

The main steps of the computing process are presented in Fig. 5.

The load transmission function C is analyzed in this part. A unit load applied on the jth deck leg will induce k_{ij} additional loads on the ith deck leg, thus the relation matrix K between deck legs (m deck legs) and deck legs (m deck legs) can be expressed below:

$$K = \begin{bmatrix} k_{11} & k_{12} & \dots & k_{1m} \\ k_{21} & k_{22} & \dots & k_{2m} \\ \dots & \dots & \dots & \dots \\ k_{m1} & k_{m2} & \dots & k_{mm} \end{bmatrix} \tag{3}$$

Meanwhile, the unit load applied on the jth deck leg will also induce z_{rj} additional loads on the rth pile–head, thus the relation matrix Z between deck legs (m deck legs) and pile–heads (n piles, including skirt piles) can be expressed below:

$$Z = \begin{bmatrix} z_{11} & z_{12} & \dots & z_{1m} \\ z_{21} & z_{22} & \dots & z_{2m} \\ \dots & \dots & \dots & \dots \\ z_{n1} & z_{n2} & \dots & z_{nm} \end{bmatrix} \tag{4}$$

The elements of the matrix K and Z are additional forces induced by unit values of the additional loads on the deck legs. That is, K and Z depend on the properties of the jacket structure.

The additional loads X transmitted to the deck legs from the additional upper loads are expressed as $X = \begin{bmatrix} x_1 & x_2 & \dots & x_m \end{bmatrix}^T$. According to Eq. (3), the additional loads $\Delta F = \begin{bmatrix} \Delta f_1 & \Delta f_2 & \dots & \Delta f_m \end{bmatrix}^T$ on the deck legs, which can be directly monitored and used to represent the additional upper loads in this paper and can be calculated by the equation:

$$\Delta F = KX \tag{5}$$

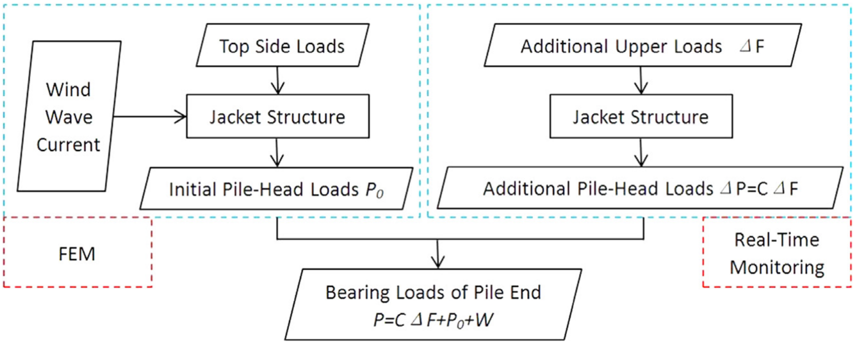

Fig. 5. Bearing loads of pile end calculation procedure.

where

$$\Delta F=\begin{bmatrix}\Delta f_1\\ \Delta f_2\\ \cdots\\ \Delta f_m\end{bmatrix},K=\begin{bmatrix}k_{11} & k_{12} & \dots & k_{1m}\\ k_{21} & k_{22} & \dots & k_{2m}\\ \dots & \dots & \dots & \dots\\ k_{m1} & k_{m2} & \dots & k_{mm}\end{bmatrix},X=\begin{bmatrix}x_1\\ x_2\\ \cdots\\ x_m\end{bmatrix}$$

Similarly, the additional pile–head loads can be calculated by the equation:

$$\Delta P = ZX \tag{6}$$

Solving Eq. (5), we obtain

$$X = K^{-1}\Delta F \tag{7}$$

Substituting in Eq. (6), the additional pile–head loads can be obtained:

$$\Delta P = ZK^{-1}\Delta F \tag{8}$$

Combining Eq. (1), the load transmission function can be obtained:

$$C = ZK^{-1} \tag{9}$$

For this jacket structure, the load transmission function is:

$$C=\begin{bmatrix}
0.2913 & 0.1434 & 0.0599 & -0.004 & 0.1488 & 0.0902 & 0.0111 & -0.038\\
0.0823 & 0.1804 & 0.0627 & 0.0410 & 0.0514 & 0.0799 & 0.0256 & 0.0161\\
0.0431 & 0.0609 & 0.1835 & 0.0817 & 0.0159 & 0.0260 & 0.0775 & 0.0525\\
-0.004 & 0.0569 & 0.1526 & 0.2897 & -0.041 & 0.0115 & 0.0866 & 0.1525\\
0.1536 & 0.0737 & 0.0211 & -0.020 & 0.3102 & 0.1323 & 0.0364 & 0.0036\\
0.0506 & 0.0560 & 0.0287 & 0.0231 & 0.0981 & 0.1845 & 0.0491 & 0.0502\\
0.0257 & 0.0259 & 0.0599 & 0.0478 & 0.0485 & 0.0508 & 0.1796 & 0.1014\\
-0.021 & 0.0174 & 0.0757 & 0.1517 & 0.0015 & 0.0377 & 0.1352 & 0.3039\\
0.2059 & 0.1692 & 0.1062 & 0.0545 & 0.1760 & 0.1402 & 0.0640 & 0.0228\\
0.0566 & 0.1006 & 0.1747 & 0.1977 & 0.0231 & 0.0661 & 0.1398 & 0.1816\\
0.1741 & 0.1268 & 0.0714 & 0.0274 & 0.2087 & 0.1581 & 0.0822 & 0.0588\\
0.0317 & 0.0684 & 0.1355 & 0.1710 & 0.0533 & 0.0848 & 0.1579 & 0.2113
\end{bmatrix} \tag{10}$$

The bearing loads of each pile end can be calculated using Eq. (2).

The additional loads ΔF on the deck legs can be gained through monitoring the strain variation and be calculated by the following equation (Wang et al., 2010):

$$\Delta F = -S \times E \times \frac{(\Delta\varepsilon'_1 + \Delta\varepsilon'_2{}')}{2} \tag{11}$$

where, S is the cross sectional area of the deck leg, E is the elastic modulus of the deck leg;$\Delta\varepsilon'_1$,$\Delta\varepsilon'_2$ is the strain variety of any two points on the deck leg diameter, measured by the strain gauge.

3.2. Early warning conditions

If the bearing loads of pile end exceed the capacity of the pile, bearing failure even sliding failure would occur. Monitoring the bearing loads of pile end and keeping an adequate safety margin is in need to prevent the pile failures, however, it is difficult to determine the safety margin. A usual method is taking a conservative value as safe as possible concerning the operational requirement of the platform, the foundation characters and so forth.

In this paper, the safety margin is determined based on the safety factors, which is required for pile design according to API RP 2A-WSD, shown in Table 2.

Therefore, a conservative value 2.0 is selected as the safety margin in this paper, that is, as soon as the bearing loads of pile end reaches half of the bearing capacity of the pile foundation, the early warning is issued.

4. Subsidence monitoring and early warning conditions

4.1. Subsidence monitoring

A little symmetrical and stable subsidence will do no harm to the structure theoretically (Dai and Shi, 2013), but the differential settlement will trigger structure damages and it is unacceptable (Wang et al. (2011)). The monitoring method of the differential settlement of the piles is discussed below.

The differential settlement will induce structure tilt, and the beam between the piles will bend correspondingly. Therefore, we can measure the strain responses at ends of the beam and tilt angel at middle to calculate the difference of elevation between any two pile tops, and then to evaluate the differential settlement.

4.1.1. Calculation for the difference of elevation of two adjacent pile tops

The beam between two adjacent piles can be simplified as a single-span beam with elastic fixed ends, and the difference of the elevation can be considered as displacement boundary condition. Initial parameter method is selected to calculate the difference of the elevation in this paper. The simplified model of the beam is illustrated in Fig. 6. Where, α_0 and α_l represent the flexibility coefficients of the elastic fixed ends; x_1 and x_2 indicate the axial locations of the strain gauges; y are the vertical distances from the neutral layer to the strain gauges; x_θ indicates the axial position of the tilt sensor; ε_1 and ε_2 are the strain values measured by the strain gauges; θ is the tilt value measured by the tilt sensor; $\varDelta$ is the difference of elevation between the two adjacent piles tops; l is the length of the beam.

Based on the initial parameter method, the initial parameter equation for this beam is established below

$$v = v_0 + \theta_0 x + \frac{M_0 x^2}{2EI} + \frac{N_0 x^3}{6EI} \tag{12}$$

where, v is the deflection of the beam; v_0,θ_0,M_0,N_0 respectively present the initial deflection, initial rotation, initial moment and initial shear at the $x=0$ end of the beam.

At the left end, where $x=0$, the displacement boundary conditions are $v_0=0$ and $\theta_0=\alpha_0 M_0$. Substituting in Eq. (12), we obtain

$$v=\alpha_0 M_0 x+\frac{M_0 x^2}{2EI}+\frac{N_0 x^3}{6EI} \tag{13}$$

After derivation calculus to above equation, we obtain

$$v'=\alpha_0 M_0+\frac{M_0 x}{EI}+\frac{N_0 x^2}{2EI} \tag{14}$$

$$v''=\frac{M_0}{EI}+\frac{N_0 x}{EI} \tag{15}$$

At the right end, where $x=l$, the displacement boundary conditions are $v(l)=\Delta$ and $v'(l)=\alpha_l M_l$. Substituting in Eq. (13), we obtain

$$\Delta=v(l)=\alpha_0 M_0 l+\frac{M_0 l^2}{2EI}+\frac{N_0 l^3}{6EI} \tag{16}$$

Moreover, substituting the tilt value θ in Eq. (14), we obtain

$$\theta=v'(x_\theta)=\alpha_0 M_0+\frac{M_0 x_\theta}{EI}+\frac{N_0 {x_\theta}^2}{2EI} \tag{17}$$

Table 2
Safety factors.

Failure mode	Safety factor
Bearing failure	2.0
Sliding failure	1.5

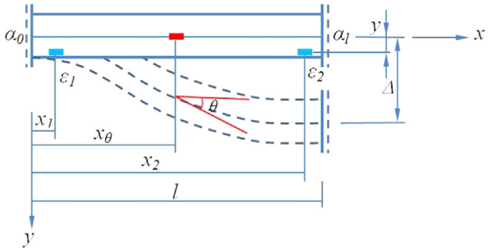

Fig. 6. Simplified model of the beam.

The relationship between the strain values ε_1, ε_2 and the curvatures can be expressed as follows:

$$\begin{cases} v''(x_1)=-\frac{\varepsilon_1}{y} \\ v''(x_2)=-\frac{\varepsilon_2}{y} \end{cases} \tag{18}$$

Substituting in Eq. (15) and solving for M_0 and N_0, we obtain

$$\begin{cases} M_0=-\frac{\varepsilon_1 x_2-\varepsilon_2 x_1}{y(x_2-x_1)}EI \\ N_0=-\frac{\varepsilon_2-\varepsilon_1}{y(x_2-x_1)}EI \end{cases} \tag{19}$$

Combining Eqs. (19), (17) and (16), and solving for Δ, we obtain

$$\Delta=\theta l-\frac{(l^2-2x_\theta l)(\varepsilon_1 x_2-\varepsilon_2 x_1)}{2y(x_2-x_1)}-\frac{(l^3-3x_\theta^2 l)(\varepsilon_2-\varepsilon_1)}{6y(x_2-x_1)} \tag{20}$$

Particularly, if $x_\theta=\frac{l}{2}$, $x_1=0$, $x_2=l$, above equation can be rewritten as follows:

$$\Delta=\theta l-\frac{(\varepsilon_2-\varepsilon_1)l^2}{24y} \tag{21}$$

Therefore, the difference of elevation of any adjacent pile tops can be calculated using Eqs. (20) and (21), and the parameters such as the strain values at ends and the tilt value at the middle can be measured easily.

4.1.2. *Calculation for the difference of elevation of any two pile tops*

Based on the calculation formula for the difference of elevation of two adjacent pile tops, it is easy to deduce the calculation method for the difference of elevation of any two pile tops. For example, the calculation method for the difference of elevation of diagonal pile tops as shown in Fig. 7 will be discussed in this part.

Where, Δ_{A1B1} indicates the difference of elevation from $B1$ to $A1$; Δ_{A2A1} indicates the difference of elevation from $A1$ to $A2$; Δ_{A3A2} indicates the difference of elevation from $A2$ to $A3$; Δ_{A4A3} indicates the difference of elevation from $A3$ to $A4$; L is the distance between A4 and $B1$.

Therefore, the difference of elevation from $B1$ to $A4$, Δ_{A4B1} can be expressed as

$$|\Delta_{A4B1}|=|\Delta_{A4A3}+\Delta_{A3A2}+\Delta_{A2A1}+\Delta_{A1B1}| \tag{22}$$

where, Δ_{A4A3}; Δ_{A3A2}; Δ_{A2A1}; Δ_{A1B1} can be calculated using Eq. (20).

4.2. *Early warning conditions*

(1) Stress requirement
In order to guarantee the operational performance of the topside, the monitoring stress cannot exceed the allowable stress. So this requirement constitutes one of the early

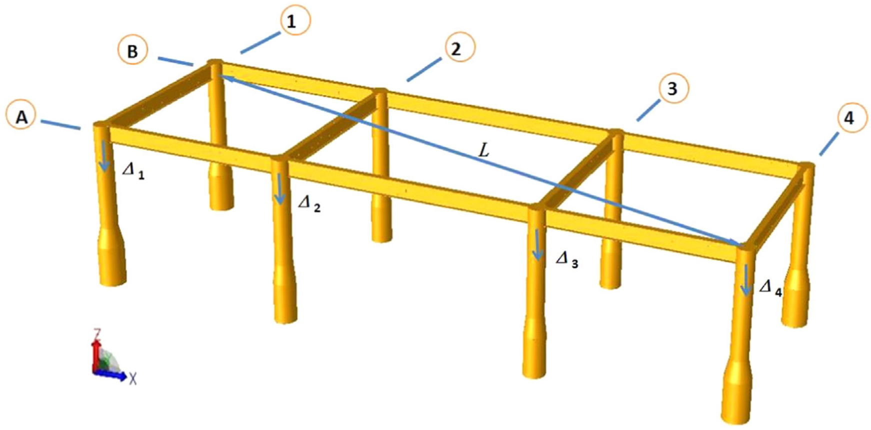

Fig. 7. Calculation model for the difference of elevation of any pile tops.

warning conditions:

$$\sigma \le [\sigma] \tag{23}$$

(2) Tilt requirement

According to requirements of related specifications (Tian and Li, 2013), the tilt of the jacket platform must be controlled within 0.3% or 0.5%, that is, if the diagonal distance of the pile tops is 20 ft, the difference of elevation cannot surpass 1in. Therefore, the fact that the difference of elevation of the diagonal pile tops must controlled within 0.5% of the distance of the diagonal piles forms another early warning condition:

$$\Delta_{AB} \le 0.5\% L_{AB} \tag{24}$$

where,

Δ_{AB} = the difference of elevation of the diagonal pile tops, can be calculated using Eq. (22);

L_{AB} = the distance of the diagonal piles.

5. Application

There is a jacket offshore platform in South China Sea. It is a self-contained 8 main piles, 4 skirts piles structure with thirty well conductors. It has been in service for over 20 years and it will serve to 2026. It is necessary to monitor the platform to guarantee the performance of the platform.

5.1. Prototype monitoring

First, the deck displacement was monitored by displacement gauge directly. There are two main ways to monitor the displacement: (1) by using GPS, but the cost is relatively high; (2) by using accelerometer to measure the acceleration and obtain the displacement by integrating the acceleration twice. In this project, the relative displacement referring to the initial state was monitored by the second way, where the acceleration was measured by fiber Brag grating accelerometer, shown in Fig. 8, whose type is HCZD400228. Besides, the displacement range is 5–45 cm, the frequency range is 0.1–10 Hz, and the acceleration resolution is 0.002 g. After a period of monitoring, the monitoring data should be cleared to reduce the accumulated error. This real-time monitoring method is feasible in engineering practice.

Second, the additional upper loads will induce the compression of the deck leg, and the strain response of the deck leg is sensitive and linear. Thus the additional upper loads can be monitored by measuring the strain responses of the deck legs. As presented in Fig. 9, the strain gauge was installed on the surface of the pile to monitor the additional upper loads acting on it.

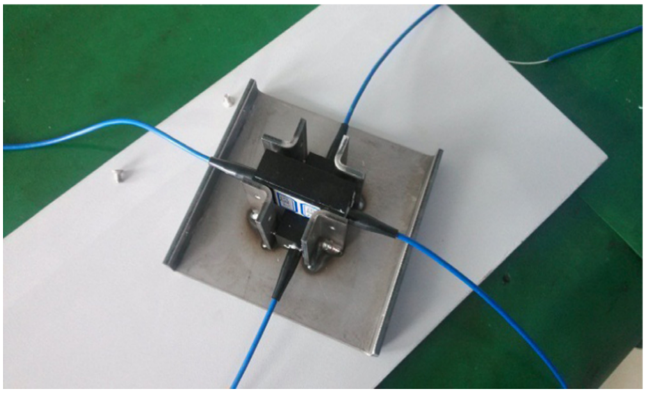

Fig. 8. Fiber brag grating accelerometer.

Fig. 9. The strain gauge on the surface of the pile.

Finally, the differential settlement was monitored through measuring the stress and the tilt of the beam. Some strain gauges were installed at ends of the beams and some tilt sensors were installed at the middle of the beams as shown in Fig. 10.

5.2. Discussion

Based on the information gained by the filed monitoring system, the service performance of this platform can be evaluated better. First, the monitored deck displacements are as shown in Figs. 11 and 12. Since the platform was monitored in mild sea state, the deck displacement manifested quite small. Second, the additional forces acting on the deck legs are monitored as shown in Fig. 13. Accordingly, the bearing loads of pile end are as shown from Figs. 14–16, and it is within the warning limit. Lastly, the tilt angles and the stresses of the beams are shown in Figs. 17 and 18, respectively. Based on these monitoring data, the uneven settlements were calculated and the settlements based on the reference A1 are presented in Fig. 19. It can be seen that the stresses and the uneven settlements are very little and acceptable.

6. Conclusions

Based on the characters of aging jacket platforms, the structural monitoring and early warning conditions are put forward, including the monitoring and early warning conditions of the displacement, the bearing loads of pile end and the subsidence. The conclusions are as follows:

(1) On the basis of pushover analysis, the curves of base shear force versus deck displacement are drawn. Furthermore, the

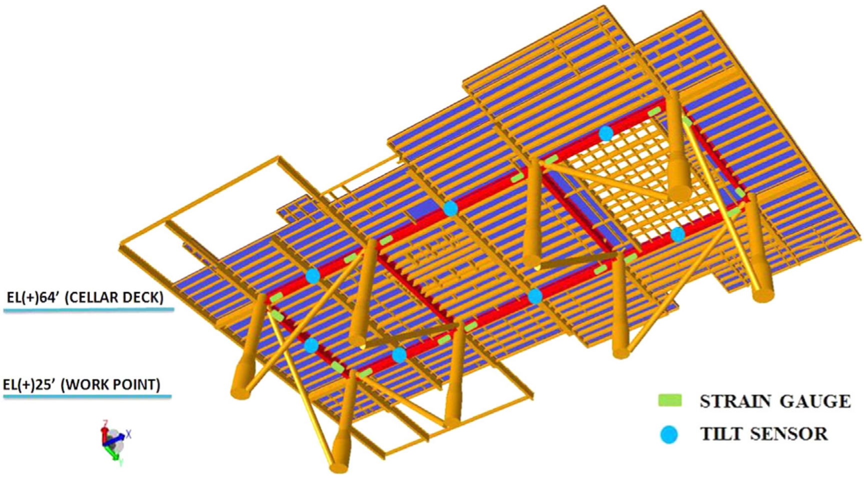

Fig. 10. Strain gauges and tilt sensors.

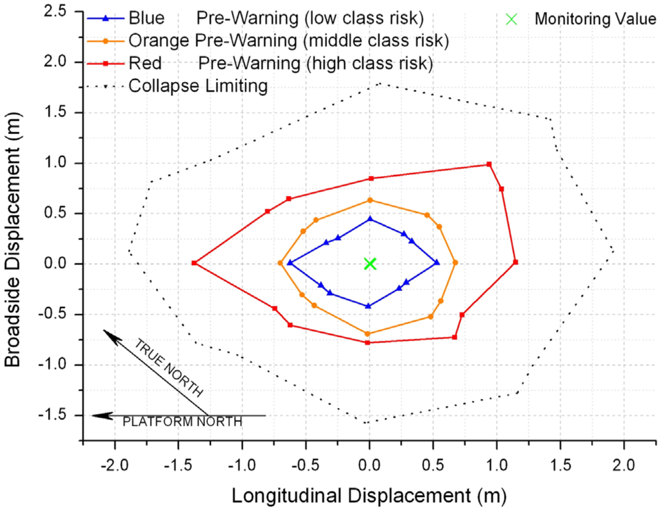

Fig. 11. The deck displacements monitored.

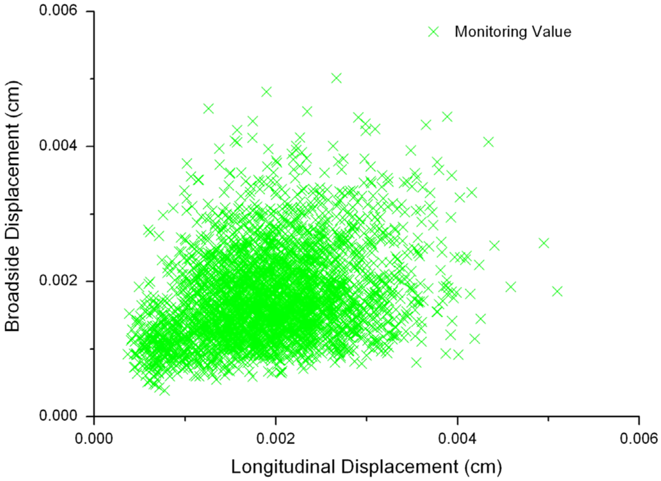

Fig. 12. The partial enlarged view of the displacements monitored.

anticipated risks were classified into three levels due to different deformations in the collapse process. Accordingly, three level early warning conditions were established.

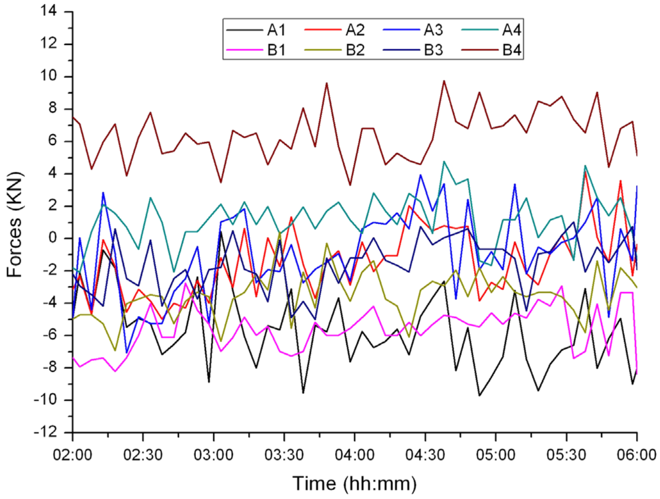

Fig. 13. The additional forces acting on the deck legs.

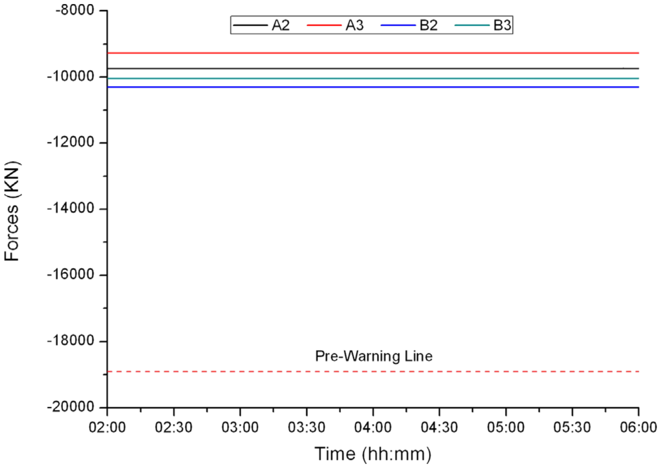

Fig. 14. The bearing loads of the inner pile end.

(2) A simple method of the monitoring of the bearing loads of pile end is put forward, with emphasis on the calculating of the load transmission function. The early warning condition that the bearing loads of pile end should not exceed half of the ultimate pile capacity is established based on API RP 2A-WSD.

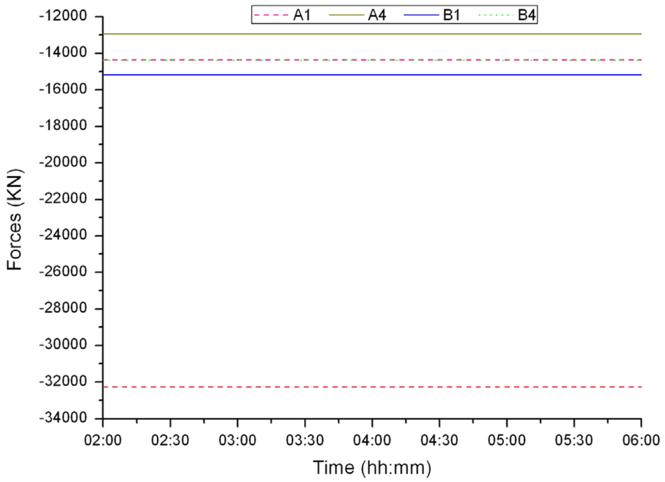

Fig. 15. The bearing loads of the outer pile end.

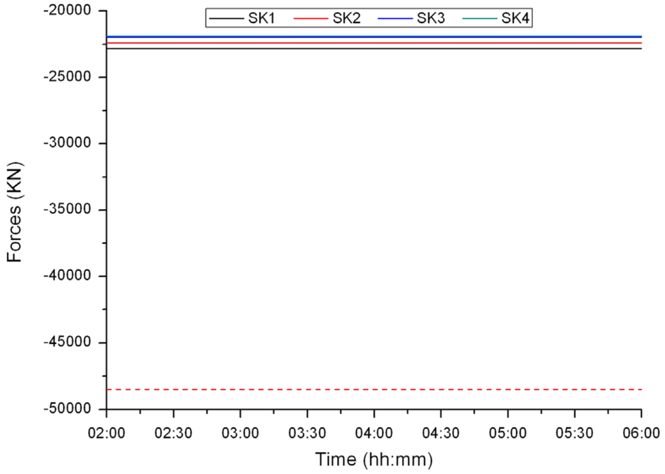

Fig. 16. The bearing loads of the skirt pile end.

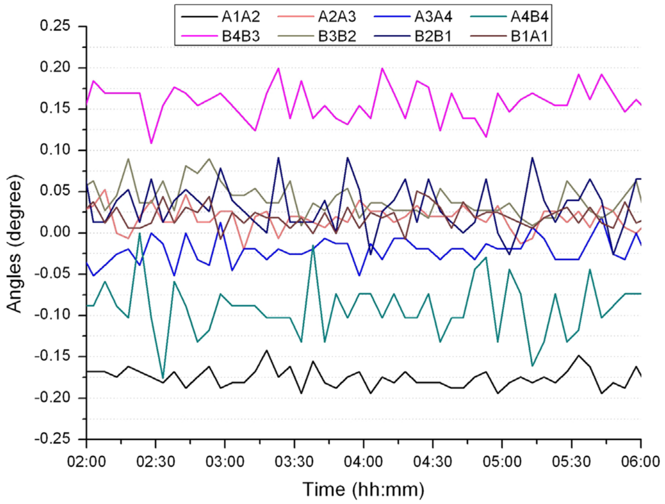

Fig. 17. The tilt sensor values.

(3) A long-term monitoring method of the subsidence of the platform was proposed, with detail discussion on the calculating of the difference of elevation between any two pile tops.

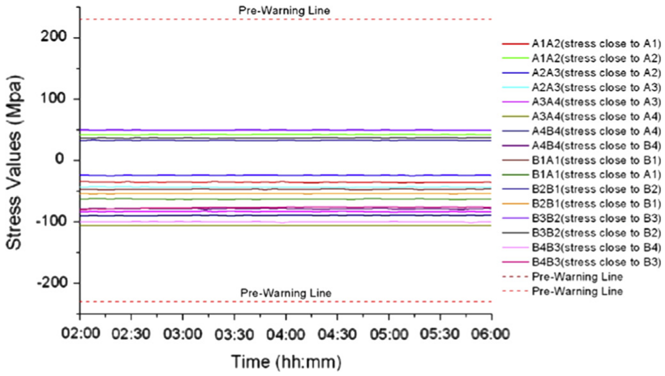

Fig. 18. The stress values.

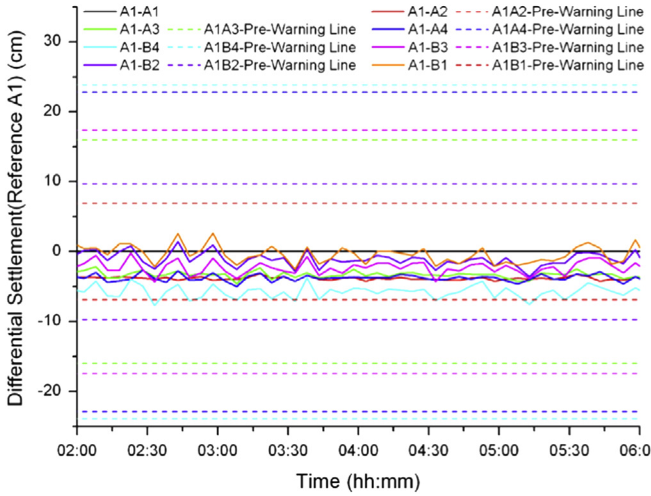

Fig. 19. Differential settlement based on the reference *A*1.

The early warning conditions considering the stress requirement and tilt requirement are established.

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