Analysis of the Influence of Tensioned Intervening Pipe on the Overall Performance of Deepwater Self-elevating Wellhead Platform

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Abstract

For deepwater jack-up wellhead platforms, a tensioner-based design scheme for tensioning the riser pipe is proposed. Based on the displacement and stress response of the riser pipe, three riser pipe sizes and corresponding tension forces were selected. Furthermore, a coupled analysis model was established between the tensioned riser pipe and the jack-up platform. Under a 550-ton tension force, the impact of three riser pipe models on the overall performance of the deepwater mobile wellhead platform was analyzed. The results indicate that the tensioned riser pipe can reduce the first two natural frequencies of the platform and mitigate the dynamic amplification effect of wave loads. As the riser pipe diameter increases, the proportion of wave loads on the riser pipe body relative to the total platform load rises, along with the load transmitted to the platform hull. While providing stiffness to the platform, the tensioned riser pipe adversely affects horizontal displacement and leg strength, with the impact becoming more pronounced as the riser pipe diameter increases. In summary, the 914×40mm tensioned riser pipe design demonstrates potential feasibility, but further optimization is required for riser strength at the mud surface, overall platform stiffness, and leg chord strength.

Keywords

Deepwater Mobile Platform (DMP); Tensioned Intervening Pipe (TIP); Wave Load; Dynamic Response; Performance Comparison.

1. Introduction

With the deepening of China's offshore oil and gas exploration, numerous marginal small-scale oil and gas structural blocks have been discovered in the western South China Sea and Bohai Sea. Due to their limited reserve scale and short development cycles, traditional development methods such as jacket fixed platforms, FPSOs, and subsea production facilities often prove economically unviable, frequently resulting in losses outweighing gains [1-2]. To address this, the author participated in designing a novel mobile wellhead platform. This platform innovatively adds a wellhead zone at the stern of traditional jack-up platforms. After positioning, lowering the riser alignment frame enables drilling and production operations similar to fixed wellhead platforms, while also allowing for pile withdrawal and relocation to new oilfield areas for continued service, akin to mobile platforms. This innovative platform combines the functions of "fixed wellhead platforms + jack-up oil production platforms," offering advantages such as reusability and low installation/disposal costs. It significantly reduces investment and operational costs in oilfield development, making marginal oilfield development economically feasible [3].

This innovative platform has been successfully deployed at the Weizhou marginal oilfield in China's South China Sea [4]. However, its operational depth is limited to shallow waters below

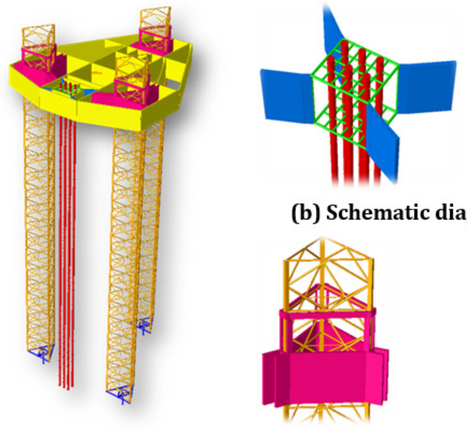
45 meters, rendering it inadequate for deep-water marginal oilfield development. To address the growing demand for deep-water marginal oilfield exploitation in China, this study proposes expanding the design depth of mobile wellhead platforms. Building upon the existing 120-meter self-elevating platform design, the research explores the feasibility of incorporating a wellhead isolation pipe, aiming to provide practical guidance for China's deep-water marginal oilfield development.

For deepwater mobile wellhead platforms, the effective support scheme of isolation pipes becomes crucial in design due to the more complex and severe environmental loads they encounter [5-6]. Traditional pipe rack alignment methods, with their numerous components, would significantly increase wave currents on the platform, adversely affecting its performance. Another potential solution is to adopt the support method of deepwater floating drilling isolation pipes [7], where constant tension tensioners are used to suspend the isolation pipes. However, no existing literature has studied this novel approach. To address this, this paper first investigates the response patterns of different isolation pipe models under varying tension forces, selects three commonly used pipe models and their corresponding tension levels, and establishes an integrated coupling analysis model between tensioned isolation pipes and the platform. The study explores how the support scheme of tensioned isolation pipes impacts the overall platform performance. The conclusions and recommendations provided can serve as references for the design of China's 120m deepwater mobile wellhead platforms.

2. Overall coupling analysis model of wellhead platform

2.1. Finite Element Model and Environmental Conditions

To investigate the impact of isolation pipes on platform structural performance, three pipe sizes (914×40mm, 762×40mm, and 508×40mm) were selected. A six-pipe layout was implemented in the wellhead area, with each pipe tensioned to 550 tons. An integrated analysis model was established for the isolation pipes-platform coupling, as shown in Figure 1(a). The wellhead configuration (Figure 1(b)) features six isolation pipes connected to the ship's upper and lower surfaces via horizontal frames. Through degree-of-freedom coupling and release mechanisms, the system simulates load transfer only in x and y directions without transmitting bending moments. Z-direction constraints are applied via tensioners. For the coupling between the platform's three pile legs and the ship's fixed pile frame: the upper and lower guide positions only couple x and y degrees of freedom, while the locking position couples the z-direction degree of freedom. All rotational degrees of freedom are released, as illustrated in the structural simulation shown in Figure 1(c).


(b) Schematic diagram of the wellhead coupling

(a) 3D view

(c) Schematic diagram of the coupling between the pile and the frame

Figure 1. Overall finite element model of the platform

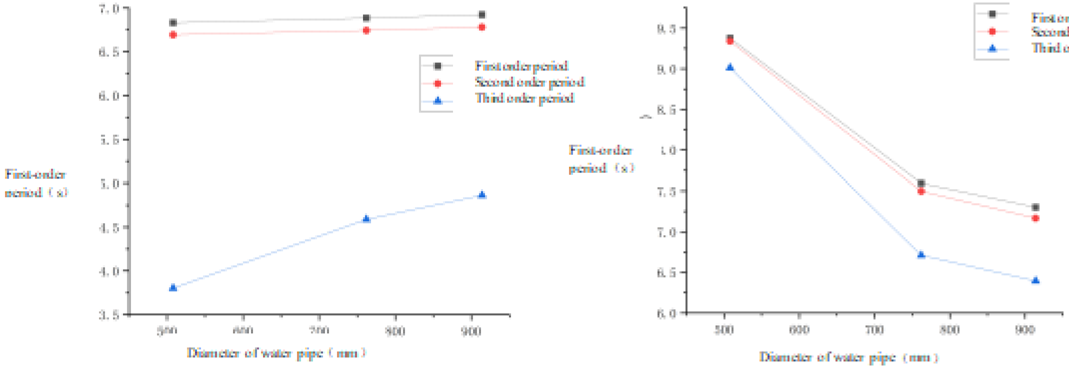
The platform's target operation is based on marine environmental factors, as shown in Table 1.

Table 1. Platform Design Environmental Conditions

environmental elements		wind speed	wave				velocity of flow (cm/s)		
		1-min	Hs(m)	Hmax(m)	Tm(s)	Tp(s)	skin layer	middle-level	ground floor
Recurrence period (years)	1	28	8.1	13.8	10.8	11.4	158	132	46
	100	50.1	13	23.1	15.2	16	268	224	81

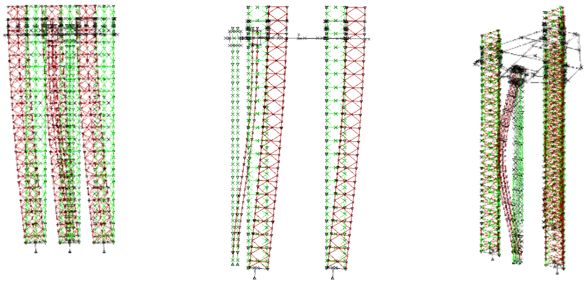
2.2. Analysis of Natural Vibration Characteristics

Using modal analysis, the natural vibration characteristics of the platform were calculated for three different types of isolation pipes, yielding the first three natural frequencies as shown in Figure 2. Figure 2(a) presents the results with additional stiffness from tension forces, while Figure 2(b) serves as a comparison without tension forces. The modal shapes corresponding to these frequencies are illustrated in Figure 3.



(a) Considering the tension effect (b) Not considering the tension effect

Figure 2. Variation of the first three natural frequencies of the platform with the scale of the water jacket



(a) First-order mode shape **(b) Second-order mode shape** **(c) Third-order mode shape**

Figure 3. Three first-order modal shapes of the platform

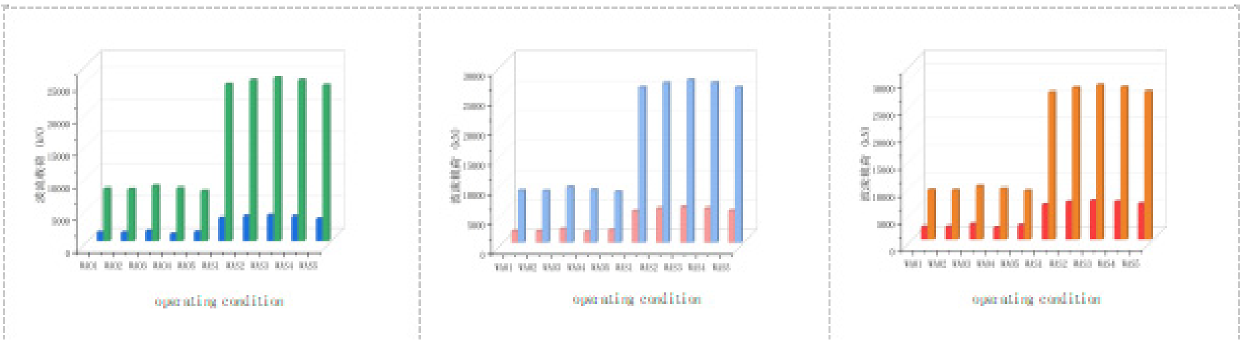
As shown in Figure 2, when the additional stiffness from tensioning force is disregarded, the first-order natural periods of the three types of isolation pipes are 7.3s,7.6s, and 9.4s respectively. These periods closely match the annual recurrence wave period (10.8s) of the platform's operating sea area. Notably, the 508×40mm isolation pipes are prone to resonance with wave loads. However, when the isolation pipes are supported by top tensioners, the platform's natural period decreases to below 7s (as illustrated in Figure 2(a)), owing to the stiffness contribution from the tensioned isolation pipes. This modification significantly reduces the platform's dynamic amplification load.

Observing the pattern in Figure 2(a), the first two natural frequencies of the platform show only slight increases with the diameter of the isolation pipe, while the third frequency increases significantly. This contrasts with the trend in Figure 2(b), where frequencies decrease as the pipe diameter increases. The modal analysis in Figure 3 reveals that the first two frequencies correspond to the overall structure's bending vibrations along the x and y axes, respectively, whereas the third frequency represents the isolation pipe's own bending vibration. This indicates that under tension, the stiffness contribution of the three pipe sizes becomes less distinct. The substantial increase in the third frequency primarily stems from its modal vibration being the pipe's inherent bending motion. Larger pipe diameters result in heavier pipes, further increasing their natural frequencies. Notably, the third frequency ranges between 3.8 to 4.9 seconds, closely resembling the wave flow period—a critical factor. Therefore, fatigue damage caused by wave flow on isolation pipes should be thoroughly considered in subsequent designs.

3. Analysis of Platform Overall Performance under Different Spacer Pipe Models

3.1. Wave Load Analysis

Considering two recurrence periods (1-year and 100-year) and five wave incidence angles (0°,60°,90°,120°, and 180°), ten analysis scenarios were established. The maximum wave loads on the isolation pipe body of the mobile wellhead platform and the platform as a whole were calculated, as shown in Figure 4. In the figure, WAO1, WAO2, WAO3, WAO4, and WAO5 represent the scenarios under the five 1-year recurrence periods with different incidence angles, while WAS1, WAS2, WAS3, WAS4, and WAS5 correspond to the five 100-year recurrence period scenarios.



(a)508mm **(b)762mm** **(c)914mm**

Figure 4. Wave and current loads on the platform and riser

Figure 7 demonstrates that the platform's wave loads show minimal dependence on wave incidence angles, with peak wave flow loads occurring at 90° incidence. The 100-year return period wave load is approximately 2.5 times that of the 1-year return period wave load. Comparing Figures 4(a), 7(b), and 7(c), the total wave flow load increases with the diameter of the isolation pipes. The wave loads on pipes with diameters of 3, 5, and 10 mm account for 18%,25%, and 29% of the platform's total load, respectively, highlighting the significant impact of isolation pipes on hydrodynamic performance—particularly the 914mm diameter pipe. For future designs using large-diameter isolation pipes, it is recommended to reduce the number of pipes deployed in the wellhead area to mitigate wave flow loads.

3.2. Load Transfer Law

Since the water separation pipe is added at the stern of the platform, obviously, part of the environmental load on the water separation pipe will be transferred to the platform hull, which will affect the standing stability of the platform. Therefore, the load transferred to the platform hull under 10 working conditions of 3 water separation pipe schemes is extracted, as shown in Figure 5.

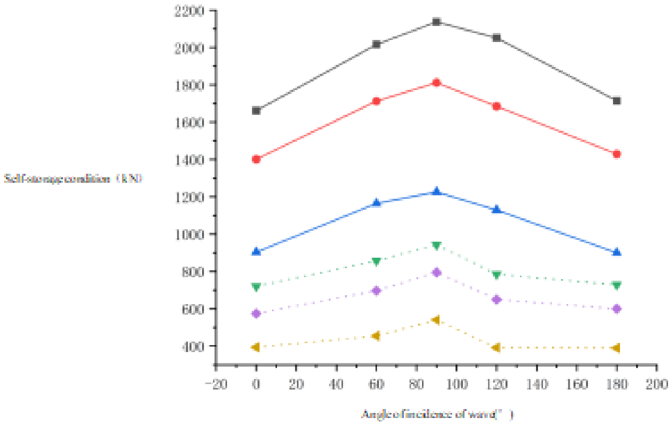


Figure 5. Load transferred to the platform hull

Figure 5 demonstrates that the load transfer from the isolation pipe to the platform follows a consistent trend across all three pipe diameters, exhibiting a pattern of initial increase followed by decrease as the incident angle of the wave increases. The load on the platform progressively increases with the isolation pipe diameter, peaking at 914mm. Under storm and self-storage conditions, the maximum transfer loads reach 943kN and 2138kN respectively, both occurring when the load incidence angle is 90°. When designing the platform hull structure, engineers should account for the load's impact on local structural strength. Additionally, the additional torque generated by this load must be considered when verifying the platform's anti-slip and anti-tilt capabilities.

3.3. Overall Displacement Response of the Platform

The platform is subjected to wind, wave, current, dynamic amplification, and P-△ loads. The wind load is calculated using the towing force formula based on the platform's wind exposure area and wind speed, while wave-current loads are determined by the Morrison formula. Dynamic amplification loads are calculated using the dynamic amplification coefficient derived from a simplified single-degree-of-freedom system. P-△ represents the additional bending moment caused by the platform's own weight, calculated according to the guidelines provided in reference [12]. Consequently, the maximum displacement response of the platform hull and the vertical displacement at the top of the wellhead isolation pipe are analyzed under the three scenarios, as shown in Figure 6.

Figure 6 demonstrates that as the diameter of the isolation pipes increases, the platform's horizontal displacement progressively rises. This occurs because larger isolation pipes, while enhancing platform rigidity, also experience greater environmental loads, leading to increased deformation. Under extreme conditions, the maximum displacement reaches 5.17 meters, posing a significant threat to the platform's operational safety. For deep-water mobile wellhead designs, improving the platform's overall rigidity to ensure deformation complies with design specifications or reducing the number of isolation pipes to lower the platform's horizontal load-bearing capacity is recommended. The vertical displacement of isolation pipes in the wellhead area remains relatively stable, with a maximum of 0.186 meters, indicating that tension effectively limits their vertical movement. This ensures safe installation of the Christmas tree for oil production in the wellhead area. It is advised to reserve a clearance height of over 0.2 meters for the Christmas tree installation.

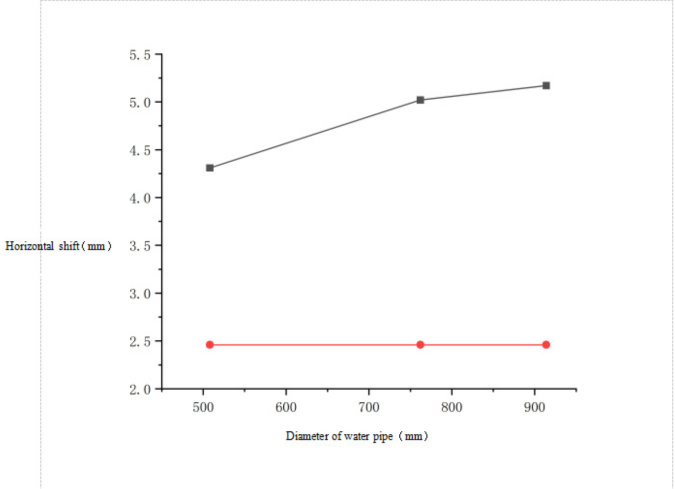
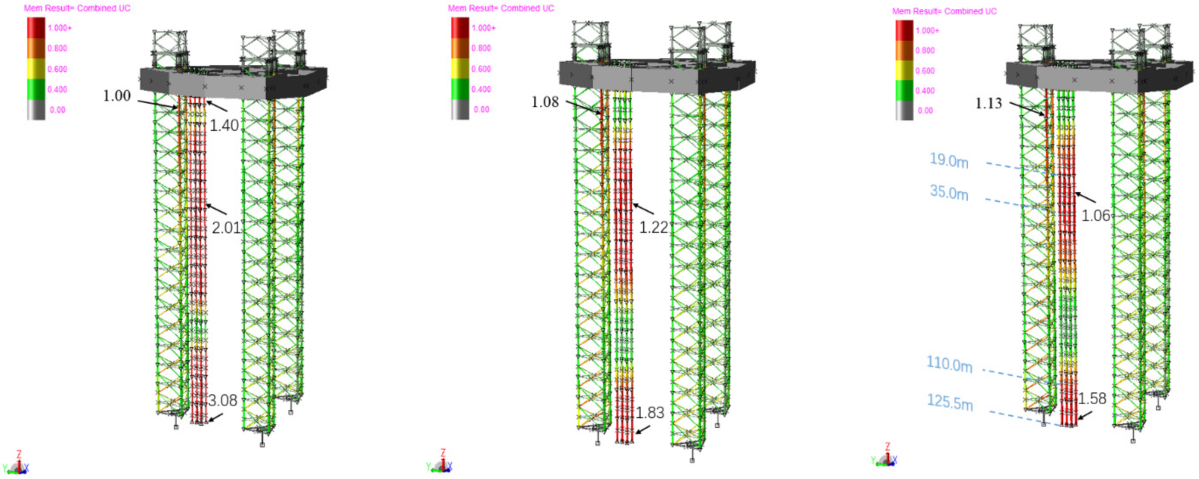


Figure 6. Comparison of displacement response results

3.4. Comparison of Structural Strength

Furthermore, the overall stress of the platform structure under three different scale of the isolation pipe was analyzed, and the cloud map of the UC value of the isolation pipe and pile leg components was checked according to the specification [13]. The results are shown in Figure 7.



(a)508mm **(b)762mm** **(c)914mm**

Figure 7. Overall UC value distribution map of the platform

As shown in Figure 7, all three spacer pipe configurations exhibit maximum UC values exceeding 1.0, indicating insufficient structural strength. The highest UC values are predominantly observed in the mid-upper and base sections of the pipes (even the top section fails to meet strength requirements when using 508mm pipes). Analysis of the UC value trends reveals that increased pipe diameter reduces UC values, with the proportion of components exceeding 1.0 gradually decreasing. This improvement stems from the enhanced strength provided by larger pipe dimensions. When the pipe size reaches 914mm, the mid-upper section's maximum UC drops to 1.06, marginally exceeding specifications and meeting requirements. High-stress zones are concentrated in the 19m-35m underwater range, while the base section's maximum UC decreases to 1.58. The substandard area extends below 110m underwater, as illustrated in Figure (c).

It should be noted that as the diameter of the isolation pipe increases, the corresponding surge flow intensifies, adversely affecting the strength of the platform pile legs. When using a 508mm isolation pipe, the UC value of the pile leg chord reaches 1.0, which is precisely at the critical threshold specified by the code. As the isolation pipe diameter increases, the UC value of the platform chord progressively rises. In the 914mm configuration, the UC value of the chord increases to 1.13, with the maximum value occurring in the area connecting to the main hull. This indicates that while smaller-diameter isolation pipes enhance the safety of the platform pile legs, they lack sufficient structural strength. Conversely, larger-diameter isolation pipes improve the safety of the isolation pipe itself but increase the risk of pile leg failure, necessitating reinforcement of the pile leg chord. For the design of deep-water mobile wellhead platforms, an optimal balance must be struck between the safety of the isolation pipe and the safety of the platform pile legs.

In conclusion, the application of a constant-tension tensioner and the design scheme for tensioning and supporting the platform's isolation pipes not only enhances the platform's stiffness but also negatively impacts its deformation and strength due to the increased load caused by the isolation pipes. Overall, this approach demonstrates potential feasibility, though further optimization is required for the local strength of the isolation pipes and the chord members of the platform's pile legs.

4. Conclusion and Recommendations

(1) The dynamic response analysis of a single isolation pipe column under 100-year wave load shows that the tension force of the tensioner is recommended to be 550t and the wall thickness of the isolation pipe is recommended to be more than 40 mm.

(2) The tensioned isolation pipes can reduce the natural vibration period of the platform, thus avoiding excessive dynamic amplification effect. When the tension force is the same, the influence of different isolation pipe models on the first two natural periods of the platform is not significant, but the influence on the third period is very obvious. Therefore, the fatigue problem of the isolation pipes should be paid attention to when designing the tensioned deepwater movable wellhead.

(3) When arranged in 6 wells, the wave loads on 914×40mm, 762×40mm and 508×40mm type isolation pipes are about 18%,25% and 29% of the total wave load respectively, and the loads transferred to the platform hull are about 120t,182t and 218t respectively. The influence of isolation pipes on the platform load-bearing capacity should be taken into account in the platform stability design.

(4) When the 550t tension is used to support the isolation pipes, the vertical displacement of the isolation pipes is small, which can meet the requirements of the installation of the Christmas tree. However, the increase of the wave load of the isolation pipes has a great influence on the horizontal displacement of the platform. In extreme working conditions, the displacement is as large as 5.0m. The overall stiffness of the platform is insufficient. The stiffness of the platform leg should be improved, or the number of isolation pipes should be reduced.

(5) The platform's overall strength analysis reveals that smaller diameter spacer pipes enhance leg stability, but compromise structural integrity. Increasing spacer pipe diameter reduces its UC value while elevating the platform's leg UC. The 550-ton tension force configuration demonstrates feasibility for 914×40mm models. To ensure structural integrity, reinforcement

should be applied to the 10-meter section above the spacer pipe's cement surface, with concurrent strengthening of the platform leg chord members.

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