Effects of Foundation Models on Jack-up Site Assessment

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Abstract

In order to investigate effects of different foundation models on jack-up site assessment, numerical simulation of a jack-up is presented based on fix joint, pin joint, linear springs and elastic-plastic model. The hull, leg, hull-leg connection is modelled using equivalent beam, beam element, spring element, respectively. Environmental loads, such as steady current, wind, wave, inertial load and buoyancy, are also included in the numerical model. Static and natural frequency extraction analysis of the jack-up is then performed in elevated condition. Finally, static and natural response rules are proposed for the four foundation models. The results show that, the horizontal hull displacement, maximum leg stress, loads on spudcan B and horizontal moment on spudcan A decrease as the rotational stiffness increases, while the natural frequency, vertical load and horizontal load on spudcan A increase with the increasing rotational stiffness. And the responses for elastic-plastic model are close to the pin joint. The proposed modelling and analyzing method is effective and reliable, which could provide guidance for jack-up development and assessment.

Key words: Jack-up; Fix joint; Pin joint; Linear springs; Elastic-plastic model; Numerical simulation

Jack-up is widely employed in offshore oil exploitation. With development into deeper water, the jack-up suffers from more serious environmental loads, which needs to predict its performance. The "Technical & Research Bulletin 5-5A Recommended Practice for Site Specific Assessment of Mobile Jack-Up Units" (SNAME, 2008) and ISO 19905-1 (Mike & John, 2011) are two important documents to formulate the jack-up response prediction, where foundation model is a very important problem.

In a storm condition, environmental loads, such as wind, current and wave, impose very complex loads or moments on jack-up and corresponding spudcans. A proper foundation model, which is used to simulate spudcan-soil interactions, is essential for the jack-up prediction (Cassidy, Martin, & Houlsby, 2004; Gaudin, Cassidy, Bienen, & Hossain, 2011; Cassidy, 2011). At present, fix joint, pin joint, linear springs, coupled nonlinear springs and elastic-plastic model are the most popular foundation models. However, the first three models cannot simulate the nonlinear interactions between spudcan and seabed soil (Det Norske Veritas, 2011; LI, YANG, & LI, 2010). This could be included in the coupled nonlinear springs and elastic-plastic model (Azadi, 2010; Bienen & Cassidy, 2009; Bienen, Cassidy, & Gaudin, 2009). However, little research has been done on how these foundation models affects the jack-up site assessment results.

The object of this paper is to investigate effects of different foundation models on jack-up site assessment in elevated condition. The numerical model of a jack-up, based on fix joint, pin joint, linear springs and elastic-plastic model, is presented firstly. Secondly, static responses, such as hull horizontal displacement, maximum leg stress and loads on spudcans, are studied deeply. Finally, natural frequencies and corresponding shapes of the jack-up are investigated.

1. NUMERICAL MODEL

1.1 Finite Elements

In order to meet China Classification Society (CCS) (2005) rule, the leg dimensions of Super M2 jack-up platform are redesigned. The modified jack-up is illustrated in Figure 1(a). There are three main components of a jack-up: the hull, there legs and corresponding spudcan footings. The hull is modelled with equivalent beam elements with the properties of box sections. The legs are also modelled using beam elements with actual profile sections. Each spudcan footing is modelled by fix joint, pin joint, linear

springs and elastic-plastic model, respectively, as can be seen in section 1.3. The connection between the leg and hull is modeled using spring elements, with the properties of two rotational stiffness in the horizontal direction and one translational stiffness in the vertical direction (LI *et al.*, 2010; MSC, 2007). The jack-up finite element model consists of 1973 grids and 1012 nodes. The soil friction angle is 34.9°, Poisson's ratio is 0.2, and unite weight is 17.36 kN/m^3. The leg material is ASTMA514CrQ (Elastic modulus: 200Gpa, Poisson ratio: 0.3, Yield limit: 805Mpa, Ultimate strength: 890MPa). According to CCS rule, the allowable stress of the leg is 684.25 MPa.
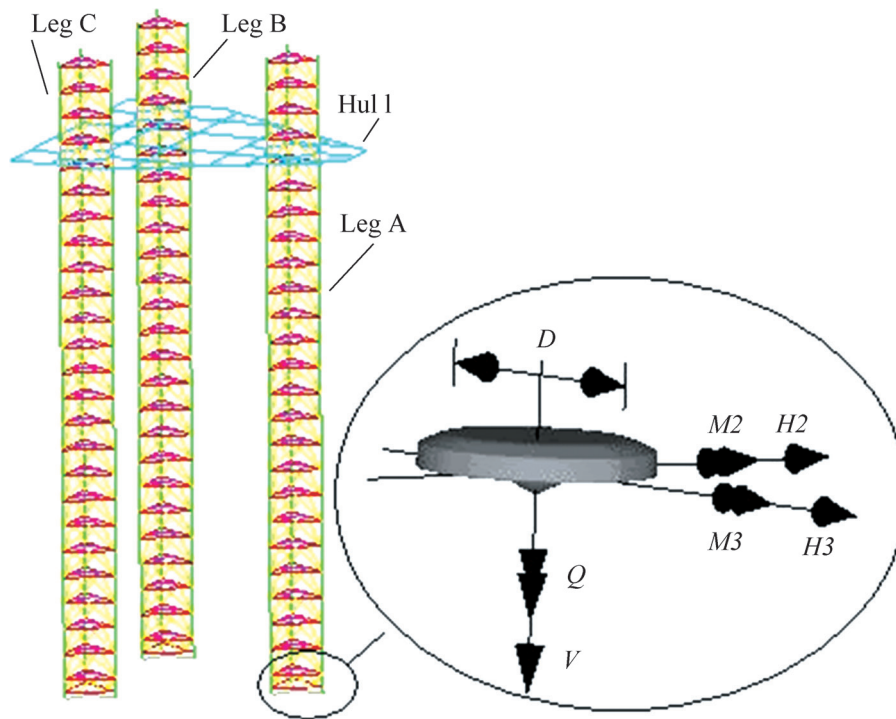
(a) Jack-up Numerical Model and Load Sign Convention of a Spudcan

(b) Loading Direction
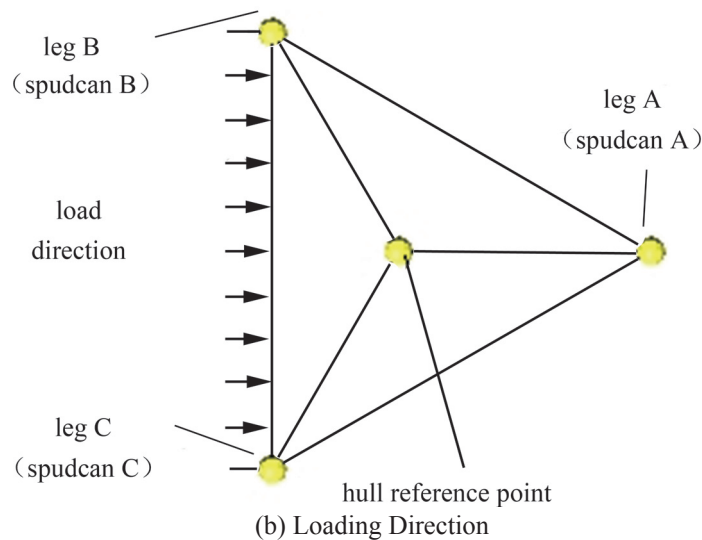
Figure 1
Numerical Model of the Jack-up Platform

1.2 Loading Conditions

The jack-up dead weight is 8500t and its preload capacity is 5769.54t. Besides that, the variable load is listed in Table 1. The elevated condition consists of survival condition and operating condition in this paper. Environmental loads applied to the analysis model are steady current, wind, wave, inertial loads and buoyancy (Table 1). Steady current loads are defined by giving steady fluid velocity as a function of elevation and location. Wind loads are applied by classical empirical formula to elements above the still water surface. Wave loads and inertial loads are provided by Morison's equation, in which Stokes fifth-order wave theory is defined. Buoyancy loads are applied to the elements immersed in a fluid. What is more, P-Δ effects are inherently accounted for in the analysis. The analysis include two steps: one step is static analysis using Newton-Raphson algorithm, the other is natural frequency extraction analysis of the structure pre-stressed in the first step. Nonlinear geometric effects are included for the first step. The environmental load direction can be seen in Figure 1 (b), in which case leg A is the leeward leg, leg B and C are the windward leg. And the hull reference point is the central point of the triangle.

Table 1
Environmental Condition and Operating Parameters of the Jack-up

	Survival condition	Operating condition
Water depth /m	91.44	91.44
Maximum wave height /m	15.24	10.67
Corresponding wave period /s	13.5	13.5
Current /(m·s^{-1})	0.89 (depth<75m)	0.54 (depth<75m)
	1.62 (depth≥75m)	1.27 (depth≥75m)
Maximum wind velocity/(m·s^{-1})	51.5	36
Air gap /m	11.28	11.28
Penetration /m	3.05	3.05
variable deck load /t	2721.6	4082

1.3 Foundation Models

Foundation models used in this paper are fix joint, pin joint, linear springs and elastic-plastic model, in which the spudcan rotational stiffness of pin joint and fix joint is zero and infinite, respectively, while the rotational stiffness of linear springs and elastic-plastic model is between the pin and fix joint. The pin joint and fix joint are relatively simple and omitted in this section. Detailed discussions are done on linear springs and elastic-plastic model (Bienen & Cassidy, 2006; Cassidy & Bienen, 2002; Simulia, 2010).

1.3.1 Linear Springs

It is assumed that plasticity does not happen on spudcan-soil interaction interface. For the six degrees of freedom model (Figure 1 (a)), the mechanical spudcan-soil interaction behavior is assumed to be as follows:

$$\begin{Bmatrix} dV \\ dH_2 \\ dH_3 \\ dM_2/D \\ dM_3/D \\ dQ/D \end{Bmatrix} = \begin{bmatrix} k_{1111} & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{2222} & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{3333} & 0 & 0 & 0 \\ 0 & 0 & 0 & k_{1212} & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{1313} & 0 \\ 0 & 0 & 0 & 0 & 0 & k_{2323} \end{bmatrix} \begin{Bmatrix} dw^e \\ du_2^e \\ du_3^e \\ Dd\theta_2^e \\ Dd\theta_3^e \\ Dd\theta^e \end{Bmatrix} \tag{1}$$

Where V, H_2, H_3, M_2, M_3 and Q is the same as loads in Figure 1, w, u_2^e, u_3^e, θ^e, and θ is its corresponding displacement. D is the effective diameter of the spudcan. k_{1111}, k_{2222}, k_{333}, k_{1212}, k_{1313} and k_{2323} is vertical elastic stiffness, horizontal elastic stiffness, horizontal elastic stiffness, elastic stiffness in bending, elastic stiffness in bending and torsional elastic stiffness, respectively. These factors could be obtained by finite element analysis, geotechnical centrifuge experiments or experiential formula. The third method is used in this paper, as follows: $k_{1111} = 2DG_{vv}/(1-v)$, $k_{2222} = k_{3333} = 16(1-v)DG_{hh}/(7-8v)$, $k_{1212} = k_{1313} = D^3G_{rr}/3(1-v)$, $k_{2323} = \frac{2}{3}DG_{vv}$, in which v is Poisson's ratio of the soil, G_{vv}, G_{hh} and G_{rr} is equivalent elastic shear modulus for vertical displacements, horizontal displacements and rotational displacements, respectively. In this paper, v, G_{vv}, G_{hh} and G_{rr} of the soil is 0.2, 51.41MPa, 3.87MPa and 5.14MPa, respectively.

1.3.2 Elastic-Plastic Model

The elastic-plastic model proposed in this paper has four major components: yield surface, elasticity, flow rule and hardening law. A yield surface in the combined loading coordinates defines the boundary of elastic and plastic states, as is shown in Figure 2. The loads within this surface result in elastic behavior (as discussed in section 1.3.1), while the loads touching the surface will result

in plastic behavior. The associated flow rule determines the ratio between plastic displacement components when plastic deformation happens. The variation of the surface size can be calculated by the hardening law.
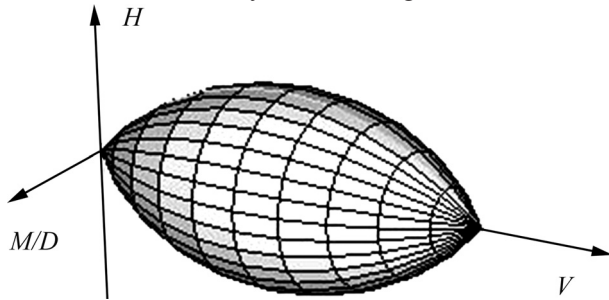
Figure 2
Yield Surface of the Elastic-Plastic Model

The yield surface for the sand case could be defined as follows:

$$f=\sqrt{\left(\frac{M}{DV_c}\right)^2+\alpha\left(\frac{H}{V_c}\right)^2}+\beta\left(\frac{V}{V_c}\right)\left(1-\frac{V}{V_c}\right)=0 \qquad (2)$$

Where V_c determines the size of the yield surface and indicates the bearing capacity of the foundation under purely vertical loading. The dimensions of the yield surface in the horizontal and moment directions are determined by α. The parameter β round off the points of surface near $V/V_c = 0$ and $V/V_c = 1$. Besides, it is well known that the parameters defining the shape of the surface do not vary greatly for the different soil types.

For a conical-base spudcan, cone portion is partially penetrated:

$$\frac{V_c}{AD\gamma}=0.3N_\gamma\left(1-e^{-\alpha\beta v_m/D}\right)+N_q\beta v_m/D \qquad (3)$$

As penetration is beyond cone-cylinder transition:

$$\frac{V_c}{AD_o\gamma}=0.3N_\gamma\alpha\beta\left(1-e^{-\alpha(v_m-v_c+\beta v_c)/D_0}\right)+ \\ N_q\left(v_m-v_c+\beta v_c\right)/D_0 \qquad (4)$$

Where γ is the soil unit weight, α and β can be derived from centrifuge data: $\alpha = 19.54\times10^{-9}\varphi^{6.129}$ $\beta=0.71-0.014\varphi$, where φ is the soil friction angle in degrees.

N_γ and N_q are classical bearing capacity factors, which can be calculated as:

$$N_\gamma = 2(N_q+1)\tan\varphi \qquad (5)$$

$$N_q= e^{\pi\tan\varphi}\tan^2(45+\frac{\phi}{2}) \qquad (6)$$

2. RESULTS AND DISCUSSIONS

Different foundation models have different spudcan loads, the horizontal hull displacement and leg stresses. Natural frequencies and corresponding shapes of the jack-up also have big differences. The main difference of the four foundation models is the rotational stiffness of the spudcan. Actually, the rotational stiffness mainly depends on the specific seabed soil-spudcan interaction property, which determines the selection of foundation models in jack-up site assessment. Detailed effects of different foundation models on the jack-up numerical simulation results are investigated deeply as follows.

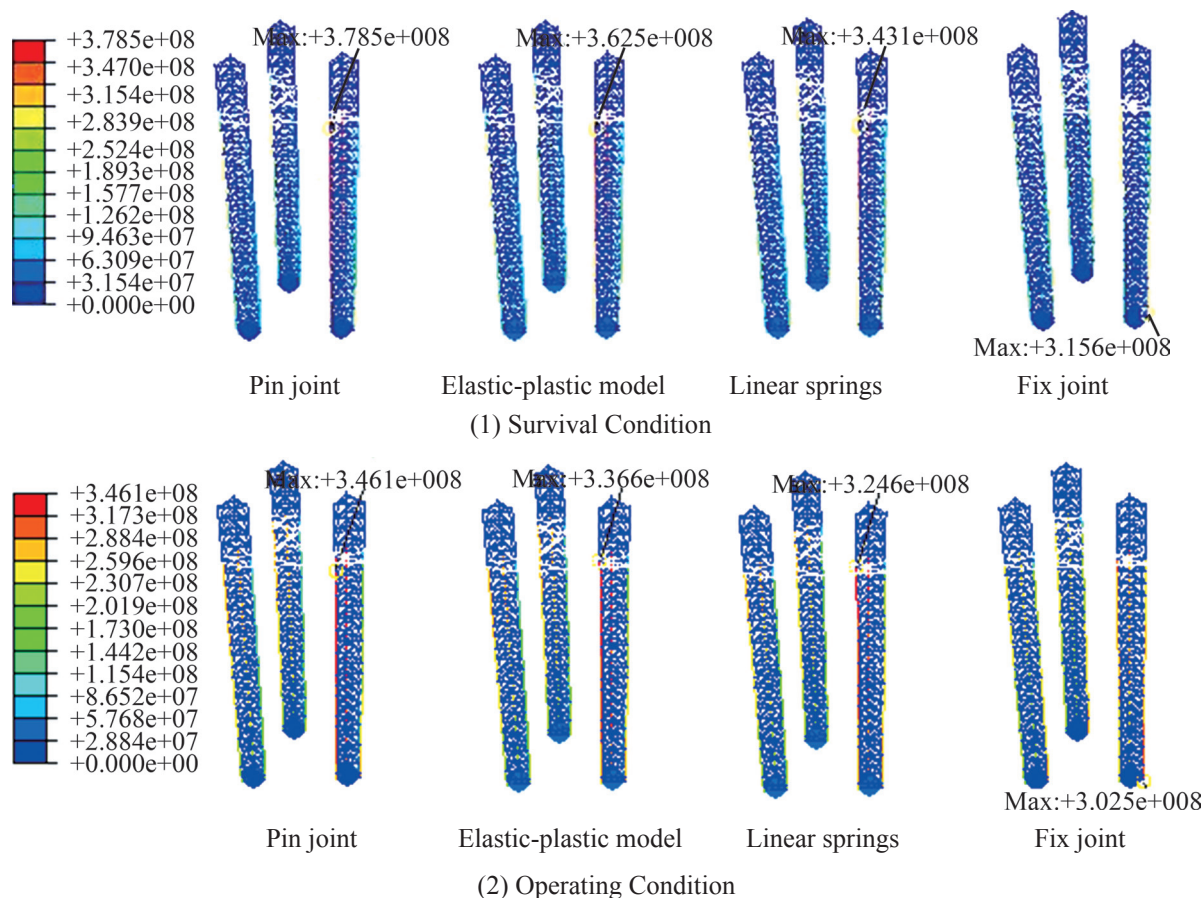## 2.1 Effects of Different Foundation Models on the Static Analysis Results

2.1.1 Displacement and Stress Analysis

All hull displacements refer to the hull reference point located at the center of the hull (Figure 1(b)). The horizontal hull displacements due to the assumed loading conditions and foundation models are listed in Table 2. The horizontal hull displacement in survival condition is nearly 1.7 times the operating condition, due to higher wind, current and wave loads. As the rotational stiffness on the spudcan increases, the horizontal hull displacement decreases significantly. The displacement for fix joint is almost 4.7 times the pin joint in elevated condition. The displacement for elastic-plastic model is close to the pin joint.

Table 2
Horizontal Hull Displacements for the Four Different Foundation Models

Elevated condition	Pin/m	Elastic-plastic/m	Linear/m	Fix/m
Survival condition	0.8948	0.8242	0.6667	0.191
Operating condition	0.5242	0.4863	0.3881	0.1095

As can be illustrated from Figure 3, the maximum von-Mises stress lies on the connecting region between the leg A and hull for pin joint, elastic-plastic model and linear springs, but close to the spudcan A for fix joint. Furthermore, as the rotational stiffness on the spudcan increases, the critical stress region translates from the upper end of the leg to the upper and lower end of the leg, and the maximum leg stress decreases significantly as well. The stress for elastic-plastic model is close to the pin joint. What is more, the leg stress in survival condition is higher than in operating condition, due to higher environmental loads.

+3.785e+08
+3.470e+08
+3.154e+08
+2.839e+08
+2.524e+08
+1.893e+08
+1.577e+08
+1.262e+08
+9.463e+07
+6.309e+07
+3.154e+07
+0.000e+00

Max:+3.785e+008   Max:+3.625e+008   Max:+3.431e+008

Max:+3.156e+008

Pin joint   Elastic-plastic model   Linear springs   Fix joint

(1) Survival Condition

+3.461e+08
+3.173e+08
+2.884e+08
+2.596e+08
+2.307e+08
+2.019e+08
+1.730e+08
+1.442e+08
+1.154e+08
+8.652e+07
+5.768e+07
+2.884e+07
+0.000e+00

Max:+3.461e+008   Max:+3.366e+008   Max:+3.246e+008

Max:+3.025e+008

Pin joint   Elastic-plastic model   Linear springs   Fix joint

(2) Operating Condition

Figure 3
Stress Profiles of the Jack-up Leg in Elevated Condition/Pa

2.1.2 Spudcan Loads Analysis

Since the loading direction is symmetric in the analysis, loads on spudcan B are equal to spudcan C. Therefore, only loads on spudcan B and A are used to be analyzed in this section. Spudcan Loads, such as vertical load (M), horizontal load (H), horizontal moment (M), are illustrated in Table 3. The maximum vertical load can be used to obtain and verify preload capacity of the jack-up. Horizontal load is one of the most important reasons for jack-up sliding failure. Horizontal moment determines the leg stress distributions of the jack-up in elevated condition. Therefore, it is very meaningful for us to study these loads.

As can be seen from the table, the vertical load and horizontal load on spudcan A increase with the increasing rotational stiffness, while the loads on spudcan B and horizontal moment on spudcan A decrease with the increasing rotational stiffness. The foundation model has the greatest influence on the spudcan horizontal moments in elevated condition. The spudcan loads for elastic-plastic model are close to the pin joint. Besides that, the vertical loads in survival condition are higher than in operating condition because of high variable deck load. However, horizontal loads and moments in survival condition are lower than in operating condition, due to high environmental loads. Furthermore, the vertical and horizontal load differences on spudcan A between the survival condition and operating condition increase and others decrease, as the rotational stiffness increases on the spudcan.

Table 3
Spudcan Loads for the Four Different Foundation Models in Elevated Condition

Elevated condition	Loads	Pin	Elastic-plastic	Linear	Fix
	VA/MN	44.91	43.95	42.81	39.24
	VB/MN	28.11	28.59	29.15	30.94
Survival condition	HA/MN	0.50	0.52	0.54	0.58
	HB/MN	0.74	0.73	0.72	0.71
	MA/MNm	0.00	8.45	16.23	39.85
	MB/MNm	0.00	8.49	16.39	42.60

To be continued

Continued

Elevated condition	Loads	Pin	Elastic-plastic	Linear	Fix
	VA/MN	46.20	45.63	44.92	42.83
	VB/MN	34.59	34.88	35.23	36.27
Operating condition	HA/MN	0.26	0.27	0.28	0.29
	HB/MN	0.38	0.38	0.38	0.37
	MA/MNm	0.00	4.92	9.30	21.58
	MB/MNm	0.00	4.97	9.45	23.43

## 2.2 Effects of Different Foundation Models on Natural Frequencies

In order to investigate the effects of foundation models on jack-up modal analysis. Natural frequency extraction analysis of the pre-stressed structure in elevated condition, based on the four foundation models, is performed in this paper. The first three natural frequencies of the pre-stressed structure in the six cases are shown in Table 4. The mode shape is identical in all cases. The first three mode shapes is torsional vibration in the positive Z direction, bending vibration in the positive X direction and torsional vibration in the negative Z direction,

respectively (Figure 4). As can be seen from the table, the natural frequency increases with the increasing rotational stiffness for all cases. The frequencies for fix joint are almost 2.2 times the pin joint in elevated condition. The frequencies for the elastic-plastic model are close to the pin joint.

The natural frequency extracted in operating condition is about 90% of the survival condition in each foundation model, which is possibly because of higher leg stress and horizontal deformation in survival condition. And the frequency in the first three ranks changes slightly in all cases.

Table 4
Natural Frequencies of the Pre-Stressed Jack-up

Elevated condition	Rank	Pin/Hz	Elastic-plastic/Hz	Linear/Hz	Fix/Hz
	1	0.2163	0.2279	0.2532	0.4843
Survival condition	2	0.2276	0.2391	0.2656	0.4993
	3	0.2464	0.2634	0.2885	0.5547
	1	0.1968	0.2083	0.2330	0.4532
Operating condition	2	0.2073	0.2188	0.2444	0.4674
	3	0.2257	0.2423	0.2664	0.5198
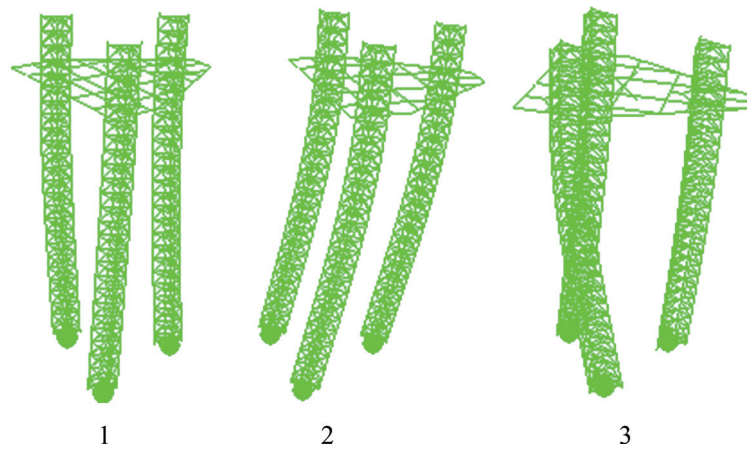
Figure 4
The First Three Mode Shapes of the Pre-Stressed Jack-up

CONCLUSIONS

(1) The horizontal hull displacement in survival condition is nearly 1.7 times the operating condition. As the rotational stiffness increases, the horizontal hull displacement decreases significantly. The displacement for fix joint is almost 4.7 times the pin joint in elevated condition. As the rotational stiffness on the spudcan increases, the critical stress region translates from the

upper end of the leg to the upper and lower end of the leg, and the maximum leg stress decreases significantly as well in elevated condition. The stress for elastic-plastic model is close to the pin joint. And the leg stress in survival condition is higher than in operating condition.

(2) The foundation model has the greatest influence on the spudcan horizontal moments in elevated condition. The vertical load and horizontal load on spudcan A increase with the increasing rotational stiffness, while

loads on spudcan B and horizontal moment on spudcan A decrease with the increasing rotational stiffness. Besides that, the vertical loads in survival condition are higher than in operating condition. However, horizontal loads and moments in survival condition are lower than in operating condition.

(3) The mode shape is identical in all cases. The first three mode shapes is torsional vibration in the positive Z direction, bending vibration in the positive X direction and torsional vibration in the negative Z direction, respectively. The natural frequency increases with the increasing rotational stiffness for all cases. The frequencies for the fix joint are almost 2.2 times the pin joint in elevated condition. The natural frequency extracted in operating condition is about 90% of the survival condition in each foundation model.

ACKNOWLEDGEMENT

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