A Simple Linear Method Applied in Mat Global Structural Analysis for Mat-supported Jack-up Rig

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Abstract. The global structural analysis for the mat-supported jack-up rig is always of the first priority since it determines the global behaviour of the platform. Different from the traditional 3-leg or 4-leg jack-up rigs, the mat-supported jack-up rig is sitting on the seabed floor instead of deeply penetrating into the seabed by the individual footing The non-linearity of the seabed soil brings more complexity to the mat global analysis. A simple linear method is introduced in this paper to solve the issues, and no non-linear elements are used. The main methodology is to use liner spring elements and iterate manually. The tension springs have to be removed after each iteration until the all the springs are in compression which is consistent with the common engineering practice that the soil is only taking compression load. Once the whole system is in equilibrium status, the normal structural assessment can be carried on in the next step. This method also helps the small offshore engineering firms reduce their cost on the purchase of those costly advanced FEM software.

Keywords: Jack-up Rig, Mat Structural Assessment Foundation Stability, Linear Spring

1 Introduction

According to the reference [1], many of the offshore oil and gas exploration is being conducted with a fleet of mobile jack-up rigs. Although there are many different mobile rig designs, the rigs can be divided into two broad categories according to their foundation type, individual footings or mat-supported.

Mat-supported rigs have a much larger bearing area and develop lower bearing pressures than rigs with independent footings. The lower bearing pressure enable mat-supported rigs to operate in areas covered by very soft clay soils with only a few feet of mat penetration below the seabed. Observed mat penetration, however, can approach the mat thickness in active delta areas around the world, such as the Mississippi River, where the soils are very soft under consolidated clay. In these cases, a simple and linear engineering methodology on the mat global analysis appears more important to help engineers quickly evaluate the foundation stability the global structural integrity of the rig.

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To illustrate the linear method, a mat with a certain length of leg is modelled in Femap (with NX Nastran Linear Solver) FEM software, and the engineering procedure and some key results are also presented in the following sections.

2 Analysis

2.1 Structure Model Description

The Mono-leg Jack-up platform consists of 3 main structural components, namely, Leg, Hull and Mat. The mat is a box-shaped structure with dimension of 40 x 40 x 4m. Structural frames and bulkheads are arranged longitudinally and transversely. Local reinforced structure is arranged around the leg to mat interface which transfer the vertical and lateral loads from the chord/bracing to the top shell, bulkheads and bottom shell of the mat structure. The leg part is a truss structure constructed with 3 chords each mounted with hydraulic type of jacking system, and x-bracing design is provided to improve leg stability.

In this paper, the focus is on the mat and part of the bottom leg as shown in the Figure 1.

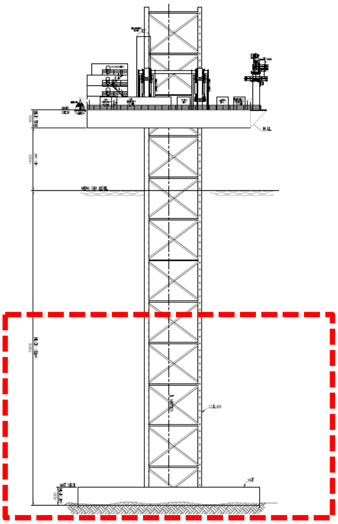

Fig. 1. Structure Model of Interest

As recommended by the reference [2], the steel material used for the construction of the jack-up mat structure is as shown in the Table 1.

Table 1. Material Properties

Item	Steel Grade	Min: Yield Strength [MPa]	Density [tonne/m3]
All Mat Plates	ABS AH/DH/EH 36	355	7.85
Column Chord and	ABS EQ47/API x65	460	7.85

Bracing			
Stiffeners and beams in Mat	ABS AH/DH/EH 36 Mild Steel	355/235	7.85
H Beam Pillar	S355JO	355	7.85

2.2 FE Model Description

According to reference[3], [4], [5]&[8], mat deck, bottom, side shells and bulkheads are modelled with plate elements. Web plates of transverse frames and longitudinal girders are also modelled using plate elements. Flanges of these frames and girders are represented by beam/bar elements. Vertical pillars supporting mat frames, and all stiffeners are modelled using beam/bar elements. The model overview is shown in the figure 2. The properties of finite elements used in the modelling are as follows:

Plate element: a combined planar shell element which typically resists membrane (in-plane), shear and bending forces.

Beam/bar element: uniaxial element with tension, compression, torsion and bending capabilities.

All elements are linear elastic isotropic material which means constant properties in all directions.

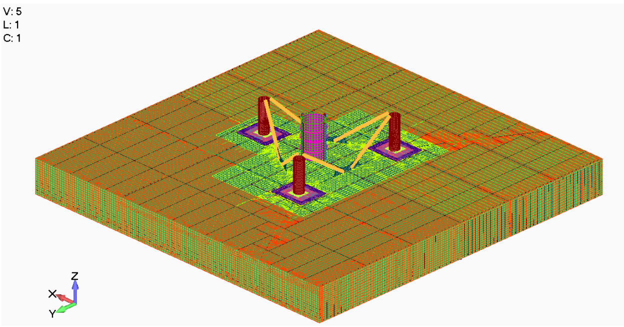

Fig. 2. Mat FE Model Overview

2.3 Boundary Condition

The seabed on which the mat rests provides compression stiffness but has no tensile stiffness. In order to simulate such a behaviour in the computer model, the linear spring elements (NX CBUSH element) are distributed at each node located on the mat bottom, and the total quantity of the spring is 21138. At the other end of spring, the pin type of fixation is applied.

For mat-supported rigs intended to rest on the sea bed, the effect of scouring and possible loss of bottom support is to be considered. This is because the soil underneath the mat, especially near the edges, is subject to the seabed current flowing, and the current may wash some soil away to form a hollow volume near the mat edge. In order to reflect this phenomenon, the class society ABS recommend consider 20%

scouring at mat bottom, and scouring is assumed to happen at two adjacent bottom edges and result in a equalized are of 35.78m x 35.78m.(1600m2x80% = 1280 m2) as shown in the Figure 3 below, blue colour indicates the area that is washed out due to scouring. The spring distribution is presented in the figure 5&6.

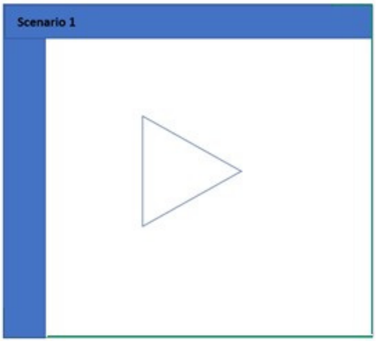

Fig. 3. Mat Bottom Scouring

Vertical: $$u_v = \left(\frac{1-v}{4GR}\right)Q \qquad (6.14.1\text{-}1)$$

Horizontal: $$u_h = \left(\frac{7-8v}{32(1-v)GR}\right)H \qquad (6.14.1\text{-}2)$$

Rocking: $$\theta_r = \left(\frac{3(1-v)}{8GR^3}\right)M \qquad (6.14.1\text{-}3)$$

Torsion: $$\theta_t = \left(\frac{3}{16GR^3}\right)T \qquad (6.14.1\text{-}4)$$

Fig. 4. Formula of Overall Spring Stiffness

The overall spring stiffness is calculated as per reference [6], and the formula is presented in the figure 4. All the input parameters and calculated spring stiffness are shown in the Table 2 and Table 3 below:

Table 2. Basic Parameters

Mat Area	1600	m2
Mat Area after 20% Scour	1280	m2
Equivalent Radius	20.185	m
Undrained Shear Strength (su)	40	kPa
Poisson's Ratio	0.5	
Rigidity Index (Ir)	200	
Elastic Shear Modulus (G)	8000	kPa

Table 3. Calculated Spring Stiffness

Overall Spring Stiffness			Individual Spring Stiffness		
			Total spring Number		21138
Vertical	1291843.8	kN/m	61.11	N/mm	
Horizontal	861229.2	kN/m	40.74	N/mm	
Rocking	350896357.8	kN/rad.	16600262.9	N/rad	
Torsion	350896357.8	kN/rad.	16600262.9	N/rad	

During the analysis, those springs found in tension will be removed after each analysis iteration until all springs are found in compression which indicates the analytical model is converged with all spring in compression.

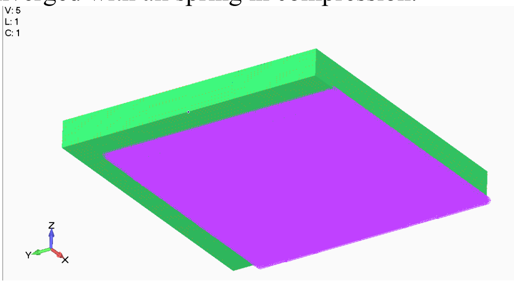

Fig. 5. Spring Boundary Condition Bottom View

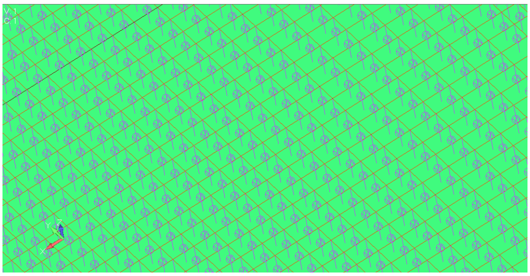

Fig. 6. Spring Element Detail

2.4 Load Application

As recommended by the reference [7], [9], &[10], the self-weight of the structure is applied by the gravity acceleration of 9.81m/s2, and load transferred from the leg, as shown in the Figure 7&8, comprises of wind, wave, current and the eccentricity of the topside load. The load actually is extracted from the Jack-up rig global in-place analysis which is not the focus of point in this paper.

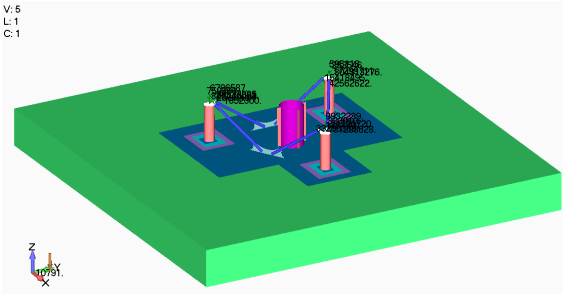

Fig. 7. Overview of Load Transferred from Leg

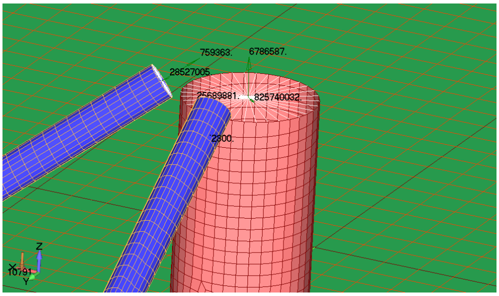

Fig. 8. Load Input Detailed View

The resultant load will cause the mat tilt in the way as shown in the Figure 9:

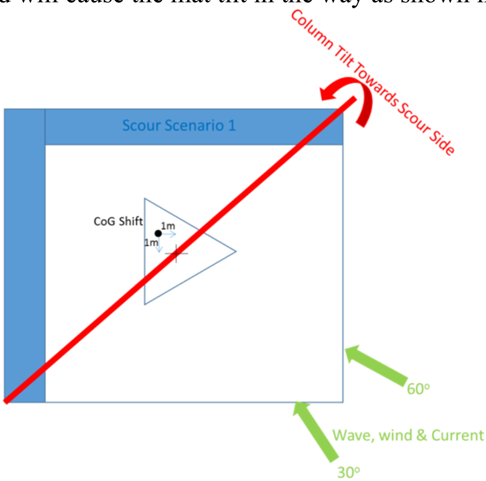

Fig. 9. Top View of Resultant Load Effect

2.5 Analysis Result

The numerical model is calculated by the NX Nastran SOL101 solver, after the initial analysis, it is found the maximum spring tension reaction is 2748N, located at the most top-right corner as shown in the Figure 10 below, and all bottom springs found in tension have to be removed （the positive legend value in the Figure 10 presents tension reaction). The next step is to conduct the second iteration analysis until the last iteration analysis where all the springs are found in compression which means the structure reach the final natural equilibrium situation. From the Figure 11 below, it is seen that all the spring reaction are in compression (negative value in the legend indicates compressive reaction), and apparently those springs located at the top-right region were removed.

From the Figure 9, it is known that the external load is causing the mat to tilt towards the scouring side, and from the Figure 10 and Figure 11, the maximum compressive reaction of the spring is found located at the most bottom-left corner, which is reasonably correct.

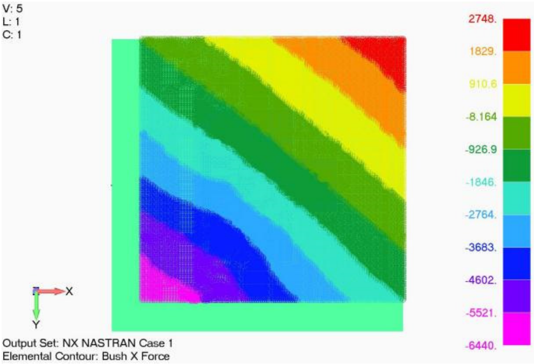

Fig. 10. Bottom View of the Spring Reaction after 1st Iteration

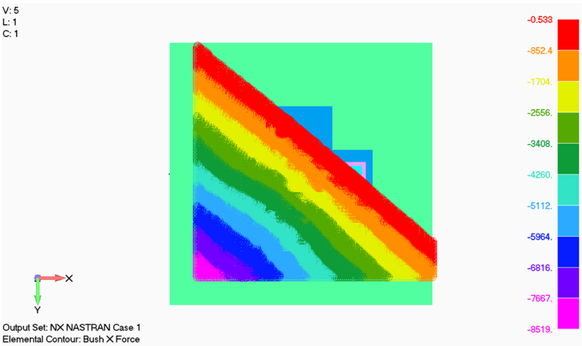

Fig. 11. Bottom View of the Spring Reaction after 5 Iteration.

Next, the mat structural assessment, such as yielding and buckling check, can be conducted as per the user's demand. The Figure 12 and Figure 13 are VonMises Stress Contour Plot for the mat structure, and the maximum stress is 334Mpa at the leg to mat interface. The detail stress assessment is not expanded into details in this paper since it is not the main focus of interest here, but the preciseness of the structural assessment result is acceptable by the class societies, and the result actually is a bit conservative.

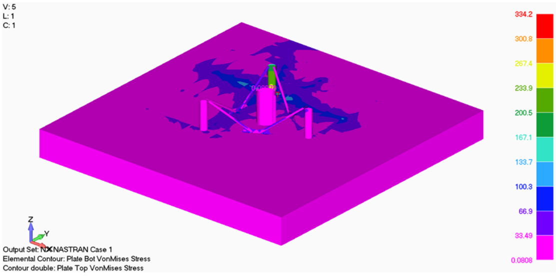

Fig. 12. Overall VonMises Stress Contour Plot

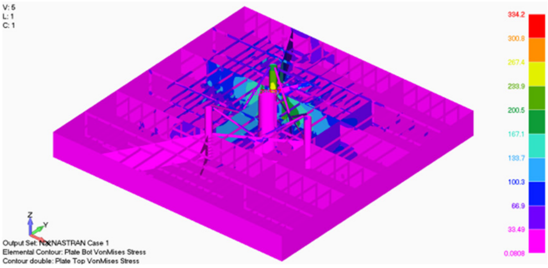

Fig. 13. Inner Structure VonMises Stress Contour Plot

3 Conclusion

This paper introduced a simple linear method to simulate the seabed soil via the linear spring. Obviously it may not be applicable to all the situation and the result may not be as accurate as other nonlinear methods, but it provides an efficient way for the small design firms or engineers to come up with a fast-track solution of the mat global structural analysis and the shallow foundation stability. The major limitation of this method is that it is only applicable to the shallow foundation of which the penetration is less than the mat depth.

In fact, the seabed soil also provide the suction force when there is a potential lift-up movement, it is suggested that the focus of future research can be given to quantifying the magnitude of suction force and the area of effect.

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