Effect of Adding Mooring Lines to the Truss Spar Platform

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ABSTRACT

A contribution of adding one more set of mooring lines to an original truss spar was examined analytically. The equation of motion was solved in time domain by using Newmark Beta integration scheme. The wave forces were calculated using modified Morison equation. The mooring lines were modeled as nonlinear springs and their restoring forces were obtained by conducting quasi static analysis. A MATLAB program was used to conduct a dynamic analysis for two cases; first for the original structure with nine mooring lines and then for the same structure with additional six mooring lines. The numerical results showed that there was no significant changes in the dynamic responses of the spar. However, the additional mooring lines play a very important role when we consider the damages to the mooring lines.

KEY WORDS: Truss spar platforms, Time domain analysis, Model tests, modified Morison equations, quasi static analysis

INTRODUCTION

As the offshore industry deplete hydrocarbon reservoirs below the sea bed in deep water depths, it is increasingly required to develop such deposits in ultra deep water. The increased water depth makes the use of fixed platforms uneconomic leaving a variety of floating platform types as the only viable options for oil and gas production operations.
One such option is the classic spar platform which has been regarded as a competitive floating structure for deep and ultra deepwater oil production. This structure is basically a very large floating vertical cylinder structure having draft around 200m and diameter around 40m. The deep-draft cylindrical spar has been shown to be an efficient platform for deep water production, drilling, and storage (Glanville et al.,). Its deep draft gives it excellent motion characteristics even in most severe sea states, which has been proved through numerical simulations, model tests and field observation. The relevant theory and comparison with experiments for this kind of spar are reported in Ran et al, Mekha et al., Cao and Zhang , and Kim et al.

Recently truss spar platforms, which are significantly modified from the conventional classic spar platforms, are being deployed in GOM. It consists of an upper circular tank, a middle truss part with some horizontal plates and a lower ballast tank at the keel. Since these two types of spars are quite different in shape, their motion characteristics are also quite different.

Research using numerical simulations has utilized the two traditional approaches namely frequency domain and time domain analysis. One such study presented by Weggel et al. uses the frequency domain technique and directly gives the statistical parameters of the spar response at relatively low computation cost. However it may be subject to large errors due to the linearization of some non-linear terms, such as the viscous term, in the equations of motion. There is evidence that this linearization probably overestimates viscous effects (Ran Z et al.). Most researchers prefer, therefore, to simulate spar motion in the time domain and this is the approach adopted in this paper.

Simulation of the motion of a spar buoy requires the definition of the equations of motion and the evaluation of all forces acting on it due to wind, current ocean waves and mooring lines. The conventional approach in offshore engineering is to use the linear form of the equations to describe the motions of rigid bodies. For large motions, the non-linear equations of motion (Chitrapu et al.) should be used but it is convenient if the exciting forces can be calculated without using wave diffraction analysis.

A key element of the analysis of a spar buoy is the evaluation of the forces and moments on it due to ocean waves and currents. One possibility to obtain these is to perform a numerical analysis of the fully non-linear interaction between the spar and its surrounding fluid. Although it is not impossible, this task require very powerful computer resources and is, therefore, not feasible in practice. An alternative approach is to carry out a diffraction analysis based on second order potential theory (see for example, Ran et al.). The computation cost of this approach is still quite high. Also this method usually generates results in the frequency domain and thereafter a transformation is needed to obtain forces in the time domain.

Another approach, often used in offshore engineering for wave force evaluation, is based on a slender body theory that requires much less computational effort and can be directly implemented in time domain analysis. In this approach, the body is assumed ‘thin’ and the force (and/or moment) is obtained as the sum of forces on each short segment of the slender body. The force in each segment is decomposed into two parts - an inviscid force and viscous drag force. One typical slender body wave force formulation is the well-known Morison equation, in which the first part is proportional to the relative acceleration and the second part to the product of the relative velocity. Rainey et al. has derived an alternative formula for the inviscid force on a slender body. His approach modifies the Morison equation by including axial divergence and centrifugal force terms acting on the spar buoy cross-section and by introducing additional point forces at the two ends of the body. All these forces are nonlinear and don’t appear in the normal Morison equation formulation. Several computation studies have been reported in the research literature using the slender body approach-all of them using different methods to calculate the inviscid force.

Chitrapu et al. [5] approximated the inviscid force by the sum of a 'Froude-Krylov' force and inertia force. The latter is evaluated in the same way as in the Morison equation but the former is estimated by the integration of the fluid pressure over the spar hull in undisturbed flow. Mekha et al. [7] considered the convective acceleration of the fluid and the axial divergence term given by Rainey et al. ([13], [14]) but showed in their case that the axial divergence term was not very important.

As done in this paper, mooring lines are commonly modelled as nonlinear springs to obtain the stiffness for the structure. This neglects the inertia of the mooring system, as well as the additional drag forces that may increase the damping of the total structure. Therefore, a better way is to analyze the spar and its mooring lines as a coupled structural system. However, this type of analysis is quite expensive.

A MATLAB program namely 'TRSPAR' was developed to determine the dynamic responses for truss spar platform using time domain analysis. Mooring lines stiffness was obtained by conducting quasi-static simulation.

This study is a part of a PhD research which is focus on the dynamic responses of truss spar platform. The main objective of this paper is to examine numerically the contribution of the mooring lines on the station keeping problem of truss spar platform.

THEORETICAL FORMULATION AND NUMERICAL SCHEME

Governing Equations

One of the most useful theories in calculating the kinematics of a progressive wave is Linear Airy theory (LAT) which is based on the assumption that the wave height (H) is small compared to the wave length (L) or water depth (d). This assumption allows the free surface boundary conditions to be linearized by dropping wave height terms which are beyond the first order and also to be satisfied at the mean water level (MWL), rather than at the oscillating free surface. For unidirectional regular waves, the first-order velocity potential is given by

$$\phi^{(1)} = \frac{ag}{\omega}\frac{\cosh ks}{\cosh kd}\sin\theta \tag{1}$$

where, g is the gravity acceleration. ω, k and a are the wave frequency, wave number and wave amplitude respectively. $\theta = kx - \omega t + \beta$.

where β is the initial phase angle.

In this study, hyperbolic extrapolation is used. It is based on the assumption that the wave kinematics between the MWL and free surface following the same LAT hyperbolic variations with depth as they do up to the MWL.

In consideration of the incident waves that are long crested and advancing in the x-direction, a spar is approximated by a rigid body of three degree of freedom (surge, heave and pitch), it derives its static resistance from support systems (mooring lines, risers) and hydrostatic stiffness.

Two coordinate systems are employed in the analysis (see Fig.1), the space fixed coordinate system oxz and two dimensional local coordinate Gζη which is fixed on the body with the origin at its center of gravity (CG). B is the center of buoyancy and F denotes fairlead.

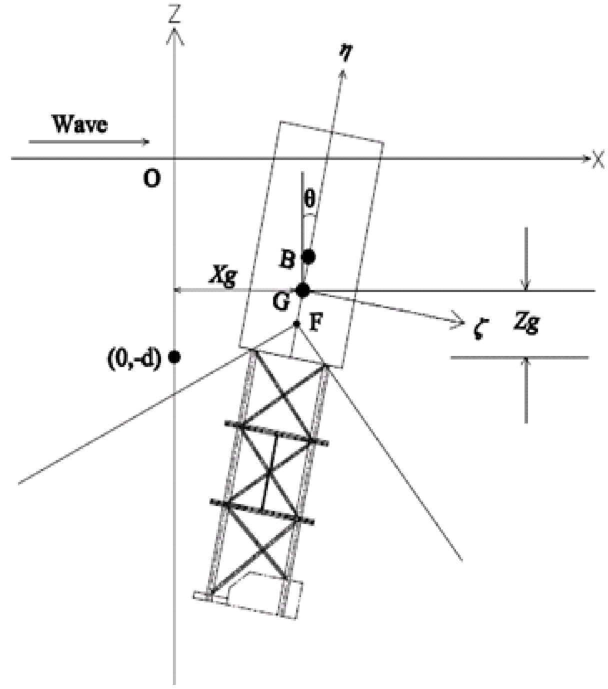


Fig. 1 Three DOF Surge-heave-pitch Model of the Spar

The wave forces are decomposed into the normal force F_{EXn} and tangential force F_{EXt}

$$\begin{bmatrix} F_{EXn} \\ M_{EX} \end{bmatrix} = \int_{-d_1}^{\varsigma} \rho(1+C_m)A(n)a_n \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn + \int_{-d_1}^{\varsigma} \frac{1}{2}\rho C_D D\left|V_n\right|V_n \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn \tag{3}$$

Where

$$a_n = \left|a - \left(a.\vec{\tau}\right)\vec{\tau}\right|$$

$$V_n = \left|V - r_s - ((V - r_s).\tau)\tau\right|$$

$$F_{EXt} = \iint \rho \frac{\partial \phi_1}{\partial t} + \frac{1}{2}\rho\left|\nabla \vartheta_1\right|^2 n_t \partial s \tag{4}$$

Cm is the added mass coefficient, C_D is the drag coefficient, V_n the relative normal velocity and $\vec{\tau}$ is a unit vector along the n-axis. a and V are respectively wave particle acceleration and velocity and r_s is strucure velocity. The tangential force can be determined by integrating the hydrodynamic pressure on the bottom surface. Φ_1 is the first potential of incident waves.

Numerical Integration Approach

All the above equations are incorporated in a MATLAB program named 'TRSPAR' for calculating the wave forces. Newmark-beta integration scheme was adopted to solve the equation of motion

$$\{M\}\left[X^{\cdot\cdot}\right]+\{C\}\left[X^{\cdot}\right]+\{K\}[X]=\{F(t)\} \tag{5}$$

Where:
$\{X\}$ is the structural displacement vector with respect to the center of gravity,

$\{X^{\cdot}\}$ is the structural velocity vector with respect to the center of gravity,

$\{X^{\cdot\cdot}\}$ is the structural acceleration vector with respect to the center of gravity,

$[M]$ is a mass matrix = $M^{SPAR} + M^{Added\ \ Mass}$

$[K]$ is stiffness matrix = $K^{Hydrostatic(hy)} + K^{Horizental\ \ Spring(hz)}$,

$[C]$ is structural damping matrix.

$[F(t)]$ is the hydrodynamic force vector and is calculated using modified Morison equation.

RESULTS AND DISCUSIONS

A numerical simulation for a typical truss spar platform was performed using TRSPAR. The physical characteristics of the original structure are summarized in Table 1. The structure has nine taut mooring lines distributed in three groups. Each mooring line consisted of a chain-wire-chain having the same geometric and material properties of the prototype mooring system, as shown in Table 2. The mooring lines were assumed to be hinged at both ends. Each mooring line was given an initial tension equal to 2312 KN.

Six mooring lines was added to the structure at the keel, as shown in Figs. 2 and 3. Time domain analysis for the particular truss spar was conducted to obtain the dynamic responses. This was done for two cases:
1. Original structure
2. Structure with additional mooring lines

The static offset tests were numerically conducted by applying variable static forces at the fairlead position. As a result, mooring line stiffness curves were obtained. Fig. 4 shows the mooring stiffness for the original and additional mooring lines. For the modified structure, it is observed that the resultant mooring line stiffness is almost twice that in the original structure.

Table 1. Physical characteristics of truss spar

Weight	389,80 ton
Vertical centre of gravity (KG)	126.34 m
Buoyancy, basic	389,80 ton
Vertical centre of buoyancy (KB), basic	152.4 m
radius of gyration for pitch	86.2 m

Regular wave with H=13m and T=16sec was used in the simulation. Although the mooring line stiffness is increased, figures 5, 6 and 7 show that there is no significan effect of adding these mooring lines to the orginal structure. However, the additional mooring lines play a very important role when we consider the damages to the mooring lines.

Table 2. Characteristics of mooring lines

	Upper section	Middle section	Lower section
Type	K4 chain	K4 chain	K4 chain
Size (m)	0.124	0.124	0.124
Length (m)	76.2	1828.8	45.72
Wet weight (kg/m)	280.5	65.4	280.5
Eff. modulus EA (Kn)	665,885	133,8915	858,925
Breaking strength (Kn)	131,89	124,55	131,89

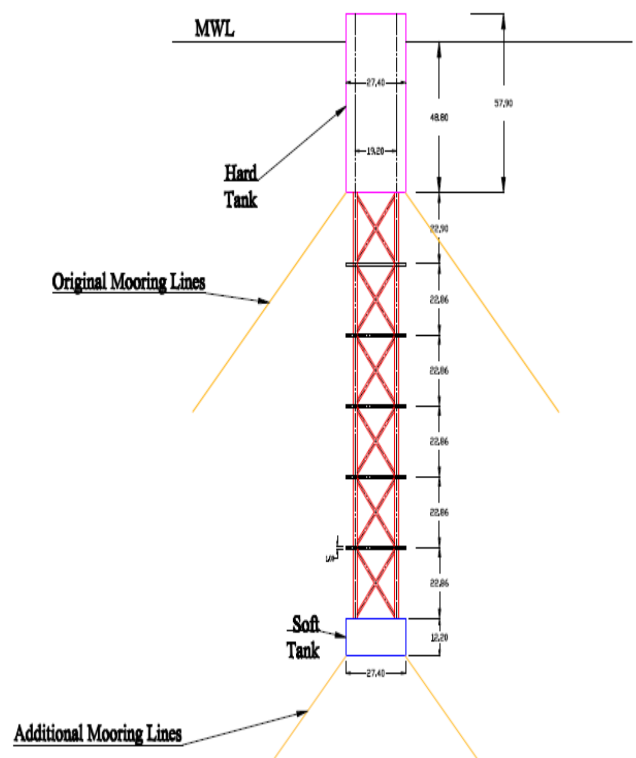


Fig. 2. Overall spar configuration with the additional mooring lines

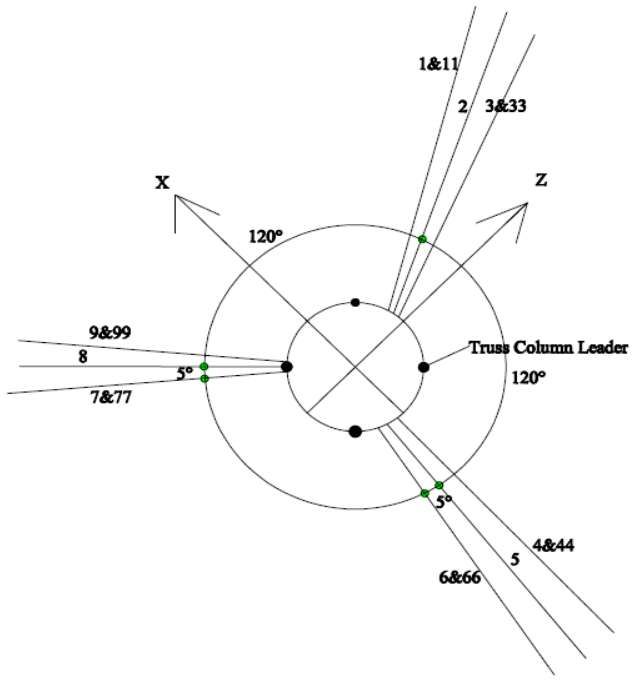
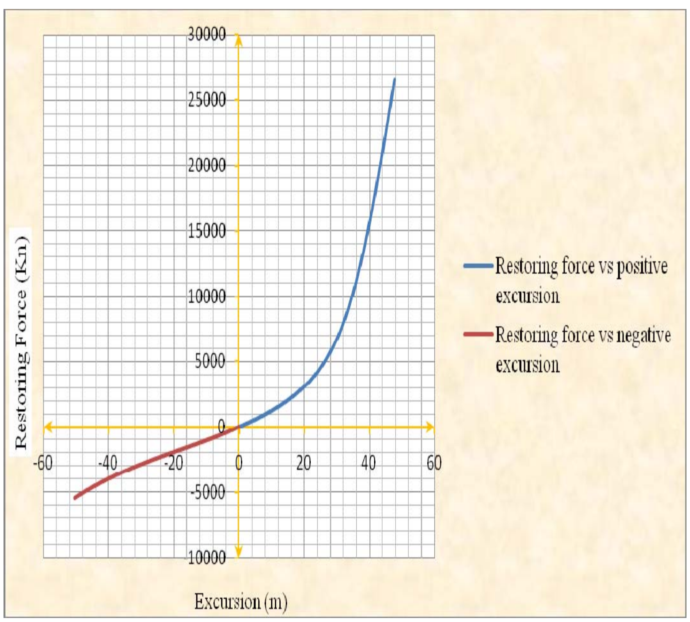
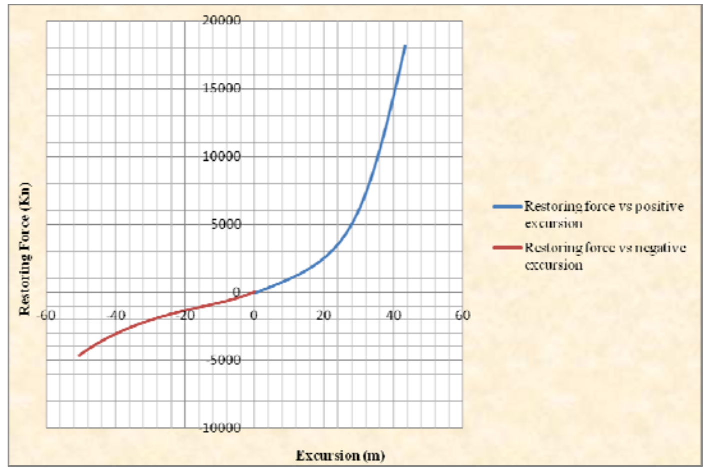


Fig. 3. Mooring lines arrangement

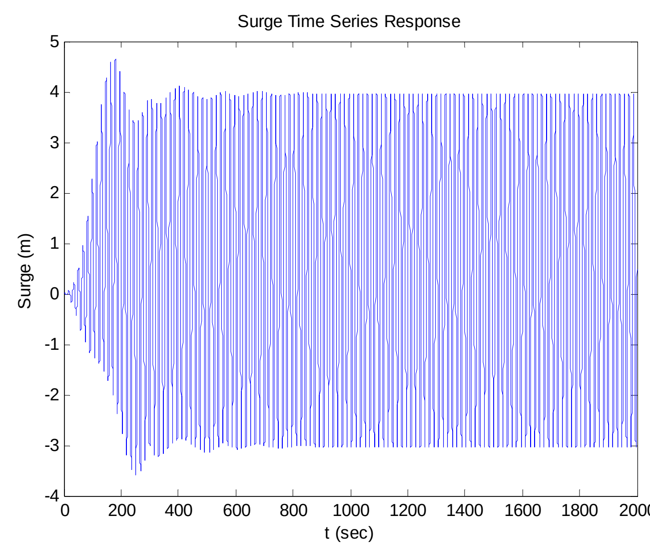


a) Surge static offset simulation for the original mooring lines..

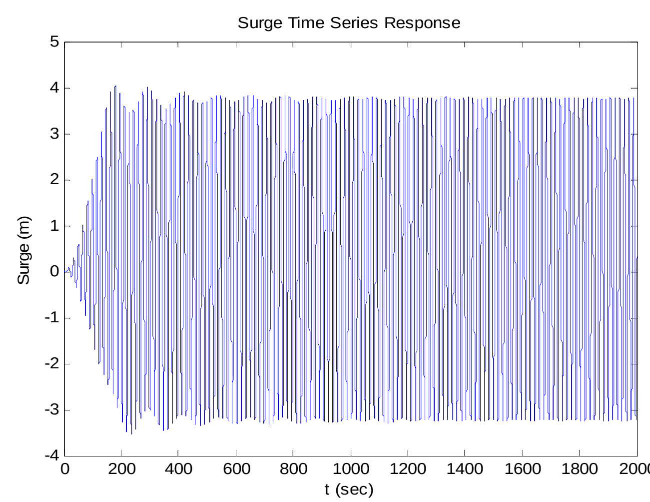


b) Surge static offset simulation for the additional mooring lines.

Fig. 4. Static offset simulation

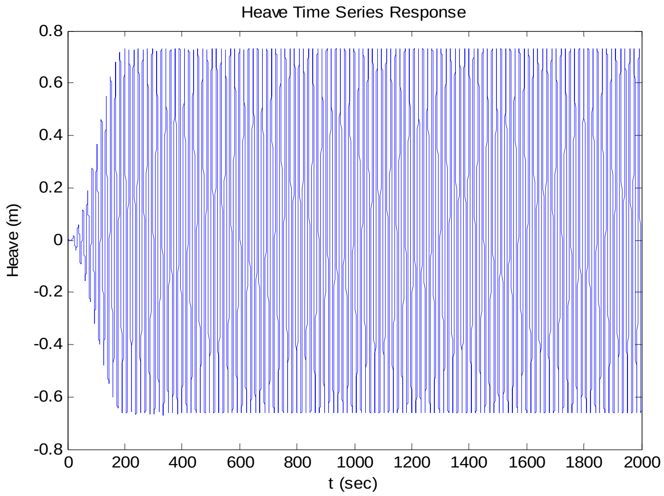


a) Surge time series –case1.

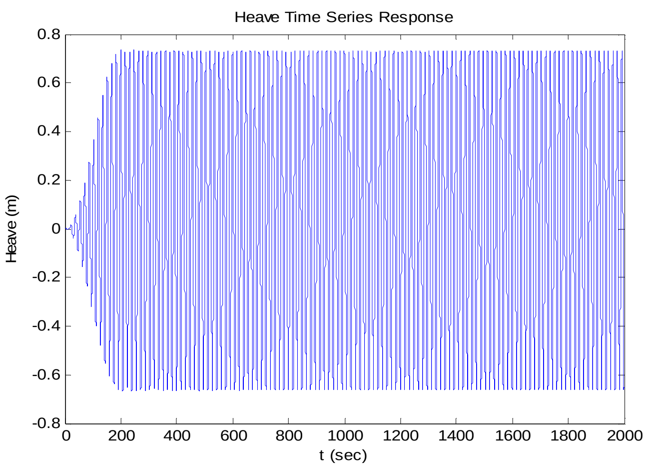


b) Surge time series –case2.

Fig. 5. Surge motion

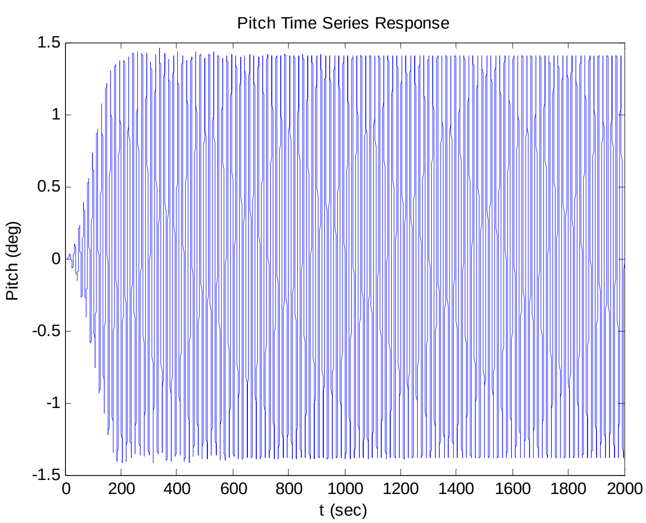


a) Heave time series –case1.

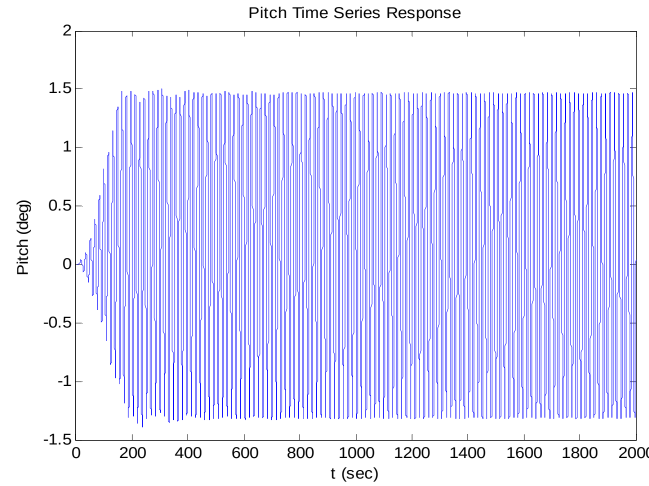


b) Heave time series –case2.

Fig. 6. Heave motion.



a) Pitch time series –case1.



b) Pitch time series –case2.

Fig. 7. Pitch motion

CONCLUSIONS

1. Numerical simulation was performed for a typical truss spar platform comparing the dynamic responses for the original structure with the structure with additional mooring lines.
2. It was found that adding mooring lines to the original structure has no significant effect on the dynamic responses. However, it may increase the redundancy of the structure when considering damage of mooring lines.

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