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# Mooring Truncation Design of a Deepwater SPAR

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**Abstract:** To solve the dimensional limitations of physical models in tests, an equivalent water depth truncated design for a classical SPAR working in 913 m water was investigated. The water depth was reduced to 736m and then to 552m. As this was done, the mooring line lengths, *EA* value, and mass per meter were adjusted. Truncation rules and formulas for parameters and truncation factors were proposed. SPAR static characteristics were made to be consistent with those at full water depth. Then further time-domain coupled analysis was carried out for the SPAR when the mooring system experienced waves. The mooring lines were simulated by quasi-static method. Global responses and mooring line forces were found to agree well with test results for a prototype at that water depth. The truncation method proved to be robust and reliable.
**Keywords:** SPAR; mooring system; truncation; global response
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## 1 Introduction

With increasing demand for oil, it is inevitable that petroleum will be extracted from deeper and deeper water. SPAR type platforms are welcome and widely used for their advantages of good dynamic response and economical fabrication, which were described by Zhang (2005, 2008) and Gu (2008). For the design of a platform, numerical simulations and model tests in offshore basin are two important methods to check its characteristics and feasibility, each with its own advantages and disadvantages. A common industrial practice is to adopt both methods in a complementary manner so that their advantages are fully exploited. But for model tests of deepwater mooring systems, the worldwide ocean basins are not large enough to simulate the whole system in reasonable model scales, and equivalent water depth truncation to mooring lines and risers and the model-the-model method is recognized to be an effective method in this field. Research on truncation design and optimization methods of different platforms has been carried out in recent years, such as Luo and Baudic (2003), Ward (2004), Stansberg (2004), Waals (2004), Baarholm (2006), Kendon (2008), Zhang *et al.* (2006) and Su (2007, 2008, 2009). “Trial and error” method, experiential formula and optimization design are common used at present. But it is still difficult to make the truncated system match very well with the full depth system. A good uniform truncation method which can adapt to most kinds of platforms has not been found, and further research on truncation methods is still expected.

Research on a SPAR mooring system working in 913 m water depth was conducted by Wichers and Devlin (2004) and Steen *et al.* (2004). Further truncation design of the same SPAR was carried out in this paper with the water depth reduced to 736 m and 552 m respectively. The relationships between main mooring parameters and the truncation factor were put forward, static characteristics of truncated SPAR mooring systems were unchanged. Coupled analysis to the whole system in the time domain were also conducted, attempting to let the global response and mooring tensions of truncation results be consistent with full depth and MARIN test results from Steen *et al.* (2004). After detailed comparison, results of the two truncation system were found correct, and the truncation design was proved to be reasonable and reliable. It is a good reference for future research in this field.

## 2 Truncation methods

### 2.1 Truncation rules

During truncation design, the static characteristics of the SPAR mooring system should be kept firstly. The mooring line length, mass in water, *EA* values, and pretensions are coordinated according to relative formulas and manual tryouts. The following truncation rules are obeyed according to Su *et al.* (2008).

1) The number, components and layout of mooring lines are consistent with full depth system;
2) The static restoring force characteristics of mooring lines are consistent with full depth system;
3) The FPSO coupled response is consistent with full depth system;
4) The representative individual mooring line’s tension characteristics are consistent with full depth system.

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### 2.2 Truncation methods

The truncation scheme is restricted by vessel type and size, components and characteristics of mooring lines, top pretension, truncation factor, etc. The following truncation method similar to Waals OJ (2004) is adopted for the SPAR mooring system.

1) Define $\gamma$ as the ratio of the truncated water depth $WD_{\text{trunc}}$ to full water depth $WD_{\text{full}}$ below fairlead, and it is also the ratio of the truncated mooring line length $L_{\text{trunc}}$ to its initial length $L_{\text{full}}$.

$$\gamma = \frac{WD_{\text{trunc}}}{WD_{\text{full}}} = \frac{L_{\text{trunc}}}{L_{\text{full}}} \tag{1}$$

Then $$L_{\text{trunc}} = L_{\text{full}} \times \gamma \tag{2}$$

2) There are three parts of every mooring line: top chain, middle wire and bottom chain. Keep the top and bottom chains unchanged, their length is $L_{\text{top}}$ and $L_{\text{bottom}}$ respectively. Only the middle wire is truncated. Define $\mu$ as the ratio of the truncated middle wire length $L_{\text{trunc-mid}}$ to its initial length $L_{\text{total-mid}}$.

$$\mu = \frac{L_{\text{trunc-mid}}}{L_{\text{total-mid}}} = \frac{L_{\text{trunc}} - L_{\text{top}} - L_{\text{bottom}}}{L_{\text{total-mid}}} \tag{3}$$

Then $$L_{\text{trunc-mid}} = \mu L_{\text{total-mid}} \tag{4}$$

3) The $EA$ and mass per meter line of middle wire after truncation are defined as $EA_{\text{trunc-mid}}$ and $M_{\text{trunc-mid}}$, which can be calculated as follows.

$$EA_{\text{trunc-mid}} = EA_{\text{ful-mid}} \times \mu \tag{5}$$

$$M_{\text{trunc-mid}} = M_{\text{full-mid}} / \mu \tag{6}$$

$EA_{\text{full-mid}}$, $M_{\text{full-mid}}$ are the original $EA$ and mass per meter line of middle wire.

4) Small changes can be made to the mooring line length until the static characteristics agree well with un-truncated system.

## 3 Frequency and time domain analysis

### 3.1 Diffraction/radiation analysis in frequency domain

Diffraction/radiation analysis is the basis for later calculations. The wave forces and harmonic response of FPSO under a series of regular waves in different periods and directions are obtained using 3-dimentional potential theory in frequency domain, such as added mass, radiation damping, first order wave force, mean drift wave force, RESPONSE AMPLITUDE OPERATORS (RAOs), etc. The equation under regular waves is as follows.

$$M_s(\omega)\ddot{x} + M_a(\omega)\ddot{x} + C(\omega)\dot{x} + K_s(\omega)x = F(\omega) \tag{7}$$

where $M_S$ is mass matrix of FPSO; $M_a$ is added mass matrix; $C$ is damping matrix; $K_s$ is stiffness matrix; $F$ is the 1st order wave forces; $x$ is RAO; $\omega$ is wave frequency.

The forces on SPAR are composed of active excitation forces and reactive forces. The active excitation forces are the 1st order wave forces, which are made up of two parts: FROUDE-KRYLOV and WAVE DIFFRACTION force, and both are assumed to be harmonic. The reactive loading is due to FPSO motions and is calculated by investigating the radiated wave field arising from body motions.

$$F_J^{(1)} = -\int_S P n_j \mathrm{d}S = -\int_S i\omega\rho(q_I + q_d) n_j \mathrm{d}S \tag{8}$$

where $F_J^{(1)}$ is active force (per unit wave amplitude) in jth direction; $q_I, q_d$ are incident wave potential and diffracted wave potential; $n_j$ is generalized surface normal to the jth direction; $S$ is wetted surface of FPSO in equilibrium.

$$F_{ji} = -\int_S iw\rho q_i x_i n_j \mathrm{d}S = -A_{ji}\ddot{x}_i - B_{ji}\dot{x}_i \tag{9}$$

where $F_{ji}$ is reactive force (per unit wave amplitude) in the jth direction, due to the ith motion; $A_{ji}$ is added mass coefficient; $B_{ji}$ is wave damping coefficient.

The mean second order wave drift forces may be calculated after the first order fluid flow problem has been solved. For the calculation, a near-field solution is adopted where forces in all six degrees of freedom are calculated. The mean wave drift forces on SPAR on the horizontal and vertical planes are calculated based on the method of direct integration of pressure acting on the wetted surface of the body. The expression for the evaluation of the 2nd order mean wave drift force $F_{\text{wave}}^{(2)}$ and moment $M_{\text{wave}}^{(2)}$ can be written as follows.

$$\begin{aligned} F_{\text{wave}}^{(2)} = & -\oint_{\text{WL}} 0.5\rho g \zeta_r^2 \boldsymbol{n} \mathrm{d}l + \iint_{S_0} 0.5\rho \left|\nabla\varphi\right|^2 \boldsymbol{n} \mathrm{d}S + \\ & \iint_{S_0} \rho\left(X \cdot \nabla\frac{\partial\varphi}{\partial t}\right)\boldsymbol{n}\mathrm{d}S + M_s \cdot R \cdot \ddot{X}g \end{aligned} \tag{10}$$

$$\begin{aligned} M_{\text{wave}}^{(2)} = & -\oint 0.5\rho g \zeta_r^2 (\boldsymbol{x}\times\boldsymbol{n}) \cdot \mathrm{d}l + \iint 0.5\rho \left|\nabla\varphi\right|^2 (\boldsymbol{x}\times\boldsymbol{n}) \mathrm{d}S + \\ & \iint \rho\left(X \cdot \nabla\frac{\partial\varphi}{\partial t}\right)(\boldsymbol{x}\times\boldsymbol{n})\mathrm{d}S + I_s \cdot R \cdot \ddot{X}g \end{aligned} \tag{11}$$

Where WL is water line along the structure surface; $\zeta_r$ is relative wave surface elevation; $S_0$ is the structure wetted surface; $X$ is the motion on structure's surface; $M_s$ is the structure mass; $R$ is the structure rotation matrix; $\ddot{X}g$ is the structure CoG acceleration vector.

The drift force coefficients (QTF) can also be calculated after diffraction/radiation analysis. The second order wave exciting force, for the general case of a spectrum consisting of more than one wave train of different frequencies, can be written as:

$$F_{sv}(t)=\sum_{i=1}^{NSPL}\sum_{j=1}^{NSPL}\left\{\begin{array}{l}P_{ij}^{-}\cos\left[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)\right]\\+P_{ij}^{+}\cos\left[-(\omega_i+\omega_j)t+(\varepsilon_i+\varepsilon_j)\right]\end{array}\right\}+\sum_{i=1}^{NSPL}\sum_{j=1}^{NSPL}\left\{\begin{array}{l}Q_{ij}^{-}\sin\left[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)\right]\\+Q_{ij}^{+}\sin\left[-(\omega_i+\omega_j)t+(\varepsilon_i+\varepsilon_j)\right]\end{array}\right\} \quad (12)$$

where $P_{ij}$ and $Q_{ij}$ are the in-phase and out-of-phase of QTF matrix, $P_{ij}$ is as follows.

$$P_{ij}^{(\pm)}=-\int_{WL}\frac{1}{4}\rho g\xi_i\xi_j\cos(\varepsilon_i\pm\varepsilon_j)\vec{n}\mathrm{d}l+\iint_{S_0}\frac{1}{4}\rho\left|\nabla\varphi_i\right|\left|\nabla\varphi_j\right|\vec{n}\mathrm{d}S+\iint_{S_0}\frac{1}{2}\rho\left(X_i\cdot\nabla\frac{\partial\varphi_j}{\partial t}\right)\vec{n}\mathrm{d}S+M_s\cdot R_i\cdot Xg_j+\iint_{S_0}\rho\frac{\partial\phi^{(2)}}{\partial t}\vec{n}\mathrm{d}S \quad (13)$$

### 3.2 Coupled analysis in time domain

The motion equation of SPAR and mooring/riser system is:

$$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+c\frac{\mathrm{d}x}{\mathrm{d}t}+kx=F_{\text{static}}+F_{\text{waveforce}}+F_{\text{slowdrift}}+F_{\text{mooring}}+F_{\text{riser}} \quad (14)$$

where $M$ is mass matrix; $c$ is damping matrix; $k$ is stiffness matrix; $F_{\text{static}}, F_{\text{wavefreq}}, F_{\text{slowdrift}}, F_{\text{mooring}}$, $F_{\text{riser}}$ are static force, wave frequency force, slow wave drift force, mooring line force, riser force respectively.

The slow wave drift force is calculated based on Newman's approximation: 1) $P_{ij}^{-}=\frac{P_i+P_j}{2}$; 2) $Q_{ij}^{-}=0$. Then equation (12) can be written as:

$$F_{\text{slowdrift}}=F_{sv}(t)=\sum_{i=1}^{NSPL}\sum_{j=1}^{NSPL}a_ia_jP_{ij}\cos\left[\begin{array}{l}-(\omega_i-\omega_j)t\\+(\varepsilon_i-\varepsilon_j)\end{array}\right] \quad (15)$$

Where $P_{ij}$, $Q_{ij}$ are the in-phase and out-of-phase components of the time-independent transfer function; $\omega_i, \omega_j$ are the frequencies of each pair of wave components; $a_i, a_j$ are amplitudes of the wave components; $\varepsilon_i, \varepsilon_j$ are random phase angles; NSPL is the number of lines into which the spectrum is divided.

The time domain motion simulation is performed for the SPAR including mooring lines and risers, which are completely coupled. Equation of motion for the SPAR in six degrees of freedom is solved during the simulation with hydrodynamic parameters, e.g. first and second order wave forces, added mass and damping, derived from the database calculated in the preceding diffraction/radiation analysis.

The quasi-static analysis method in API (2005) is used for evaluating the performance of SPAR mooring system. In this approach, the dynamic wave loads are taken into account by statically offsetting the vessel by wave induced motions. Vertical motions and dynamic effects associated with mass, damping and fluid acceleration on the mooring line are neglected. Compared with the mooring dynamic analysis, the quasi-static analysis method can save more computation time and promote calculating efficiency greatly. It is a popular and widely used method, especially during initial design of mooring system.

## 4 Truncation design of SPAR mooring system

### 4.1 Particulars of SPAR

The SPAR analyzed is a traditional vertical cylindrical structure whose working depth is 913.5 m. Its particulars are shown in Table 1, the model and mesh of SPAR are shown in Fig.1. The SPAR is anchored by 14 evenly spaced semi-taut mooring lines. The mooring lines are positioned on the outer wall of SPAR with a height of 91.44 m from the keel. Every line is made up of three parts: top chain, middle wire, and bottom chain. There are also 23 vertical risers connected to SPAR. Considering the calculating convenience, the 23 risers are simplified into one mass less equivalent riser, and its top pretension is the sum of 23 risers, the linear stiffness is small which will not affect the vertical motion of SPAR. The mooring and riser parameters are shown in Table 2 and Table 3, and their layout is shown in Fig.2, No.1~14 are mooring lines, and No.15 is the simplified riser.

**Table 1 Particulars of SPAR**

| Item | Value |
|---|---|
| Diameter / m | 37.2 |
| Draft / m | 198.1 |
| Freeboard / m | 16.8 |
| Mass / kg | $2.12819\times10^{8}$ |
| Buoyancy / N | $2.164594\times10^{9}$ |
| KG (adjusted) / m | 88.6 |
| Roll radius of gyration / m | 69.1 |
| Pitch radius of gyration / m | 69.1 |
| Yaw radius of gyration / m | 16.7 |

**Table 2 Parameters of mooring lines**

| Item | Bottom chain | Middle wire | Top chain |
|---|---|---|---|
| Length / m | 350.5 | 975.4 | 76.2 |
| Mass in water / ($\mathrm{kg\cdot m^{-1}}$) | 322.76 | 79.3 | 322.76 |
| $EA$ / N | $1.33\times10^{9}$ | $1.63\times10^{9}$ | $1.33\times10^{9}$ |
| Pretension/N | | $3.025\times10^{6}$ | |

**Table 3 Parameters of risers**

| Type | Production | Water injection | Oil export | Gas export |
|---|---|---|---|---|
| Number | 19 | 2 | 1 | 1 |
| Diameter / m | 0.348 | 0.261 | 0.435 | 0.435 |
| Pretension / N | $2.11\times10^6$ | $1.44\times10^6$ | $1.74\times10^6$ | $8.87\times10^5$ |
| Total pretension / N | $4.5523\times10^7$ | | | |
| Equivalent stiffness/($N\cdot m^{-1}$) | $1.30\times10^6$ | | | |

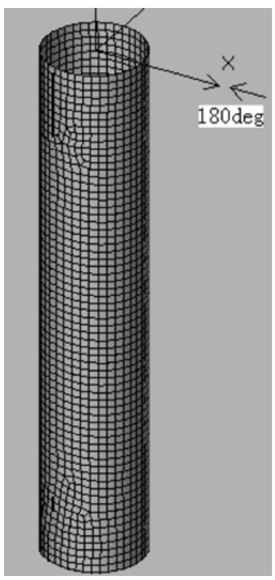


Fig.1 Model and grids of SPAR

### 4.2 Truncation scheme

Model tests of SPAR are supposed to be carried out in a deepwater basin of 50 m × 30 m × 10 m, the model scale is 1:92, which is fine for the 913.5 m water depth. Then numerical simulations are conducted as preparations for later model tests, the methods are planned as follows.

Method 1: Numerical simulation to the full water system.

Method 2: The basin depth is reduced to 8 m, the model scale is 1:92, and the truncation water depth is 736 m. Equivalent design and numerical simulation to the truncated system are carried out.

Method 3: The basin depth is reduced to 6 m, the model scale is 1:92, and the truncation water depth is 552 m. Equivalent design and numerical simulation to the truncated system are carried out.

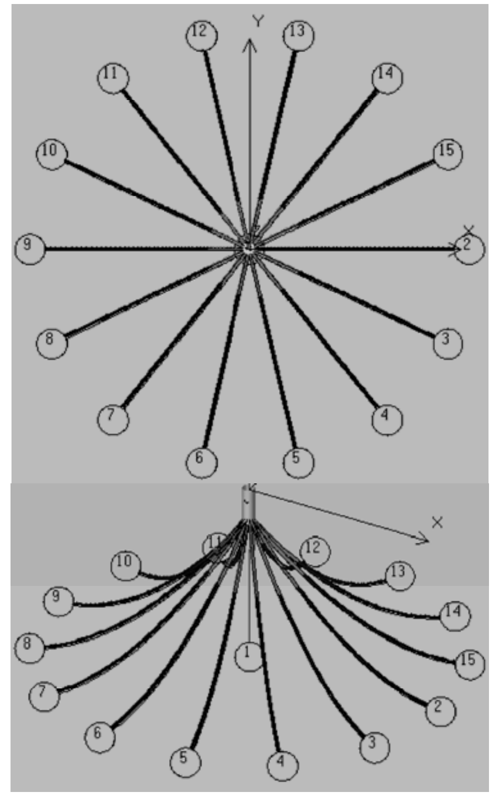


Fig.2 Mooring line and riser system of SPAR

### 4.3 The truncated mooring system

According to above truncation scheme and formulas, equivalent design of the mooring system in 736 m and 552 m water depths has been finished. The mooring parameters of truncated middle wires are shown in Table 4. The comparison of layout between that truncated mooring lines and un-truncated lines is shown in Fig.3. It is found that they match very well, and the mooring line shape and top angles are identical. The truncations are proved to be accurate.

The truncation to riser is simple, the pretension and stiffness is not changed, only the length is reduced to a certain extent.

**Table 4 Parameters of truncated middle wires**

| Item | Value | Value |
|---|---|---|
| Water depth / m | 736 | 552 |
| Length / m | 668 | 348 |
| Mass in water /($kg\cdot m^{-1}$) | 116 | 224.7 |
| EA / N | $1.11\times10^9$ | $5.88\times10^8$ |
| Pretension / N | $2.916\times10^6$ | $2.740\times10^6$ |

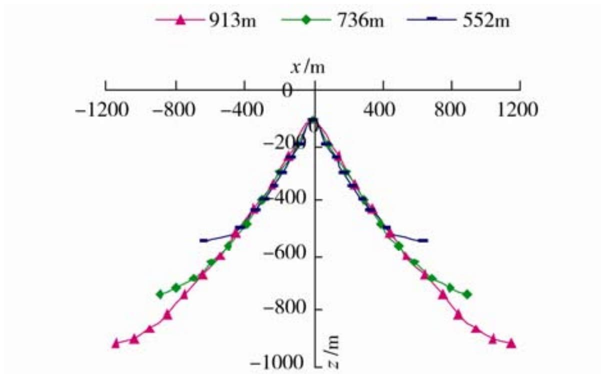


Fig.3 Layout of mooring lines in different water depths

### 4.4 Comparison of static characteristics

The curves of horizontal restoring mooring force, vertical mooring force and representative force of line1 and line8 with surge are plotted in Fig.4, Fig.5, Fig.6. All the truncation results agree well with full depth results. Since the pretensions of truncation systems are a little smaller than un-truncated system, there is difference among forces in line 8, but it is acceptable. All in all, the truncation design is successful to keep the SPAR static characteristics unchanged.

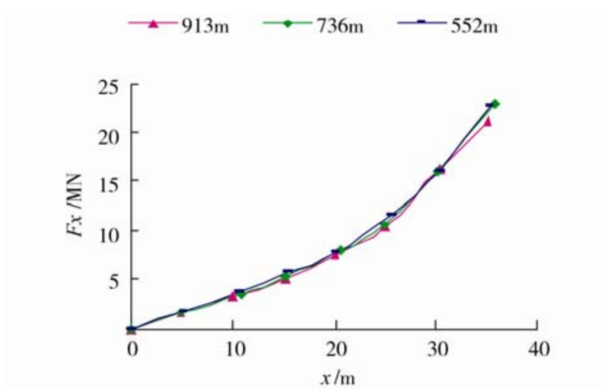


Fig.4 Curves of horizontal restoring force – surge

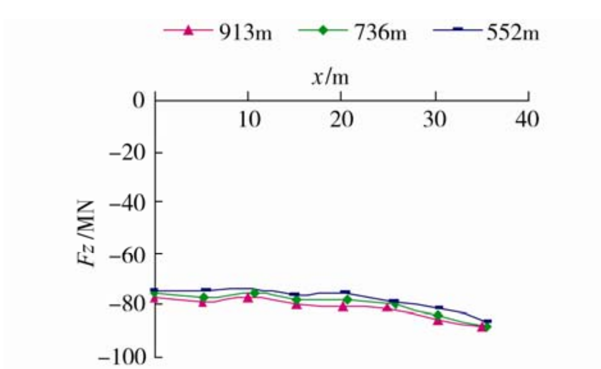


Fig.5 Curves of vertical mooring force-surge

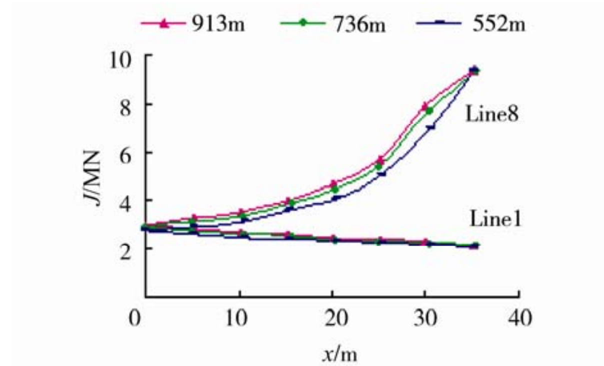


Fig.6 Curves of Line1 and Line8 mooring force-surge

### 4.5 Results of radiation/diffraction analysis

During the radiation/diffraction analysis, since the SPAR is symmetrical, the incident waves are within $0^{\circ}$~$90^{\circ}$, and the interval is $15^{\circ}$. A series of wave frequencies are selected from 0.1 to 1.4 rad/s, then the hydrodynamic coefficients, wave forces and RAOs, etc. are obtained. Since the SPAR working depth is large, the radiation/diffraction analyzed results are not affected by truncation depths at all. It can be seen from comparisons of surge and pitch RAOs with wave frequency in Fig.7.

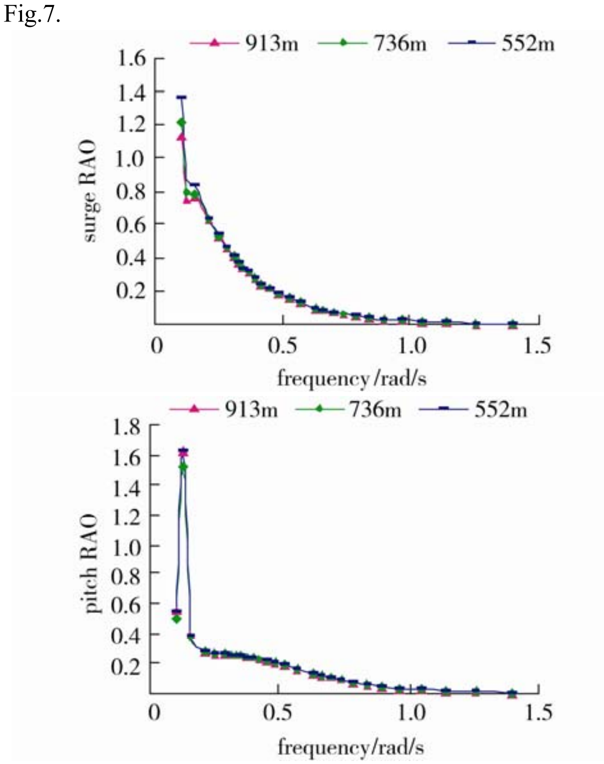


Fig.7 Comparison of surge and pitch RAOs with wave frequency when incident wave is $180^{\circ}$

### 4.6 Results of coupled analysis in time domain

A 100-year extreme hurricane environment in Gulf of Mexico is specified for this study. Only wave is considered, wind and current are ignored. The wave spectra is JONSWAP, $\gamma = 2.5$, significant wave height is 11.82 m, wave period is 14.12 s, wave direction is $180^{\circ}$.

At the beginning of time domain simulations, SPAR is placed at its equilibrium position under the mean wave force so that the initial transient motion is reduced to a minimum. The length of simulation is 3 hours and time step is 0.1 s.

Some representative calculated results of both full depth and truncated systems are listed in Table 5, they are also compared with MARIN model test results from Steen A (2004). It is found that the full depth numerical results match well with model test results in not only the extremes but also the mean values. But the extreme mooring line tensions are about 10% lower than test results, that is because the quasi-static method is used to analyze the mooring lines.

The motions of truncated systems match well with full depth results, but since the top pretensions of truncated mooring lines are lower, their maximum mooring tensions are a little smaller than full depth results. In conclusion, the truncation design is reasonable and acceptable.

**Table 5 Comparison of results**

| Response and mooring forces | | Surge / m | Pitch / (°) | Line1 / kN | Line8 / kN |
|---|---|---|---|---|---|
| Minimum | Model test | -8.20 | -4.02 | 2645 | / |
| | 913m | -8.11 | -3.8 | 2849 | 2759 |
| | 736m | -7.52 | -3.57 | 2757 | 2691 |
| | 552m | -7.44 | -3.86 | 2606 | 2536 |
| Maximum | Model test | 3.38 | 2.65 | 3785 | / |
| | 913m | 5.54 | 3.52 | 3455 | 3262 |
| | 736m | 4.86 | 3.53 | 3256 | 3119 |
| | 552m | 4.24 | 3.47 | 3042 | 2897 |
| Mean | Model test | -1.22 | -0.13 | 3140 | / |
| | 913m | -1.21 | -0.11 | 3084 | 2988 |
| | 736m | -1.26 | -0.11 | 2969 | 2879 |
| | 552m | -1.20 | -0.12 | 2780 | 2704 |

## 5 Conclusions

Through above truncation designs and numerical simulations to SPAR and its mooring system, the following conclusions can be drawn.

1) The truncation design of a SPAR mooring system has been performed, and the relations among truncation factor, mooring line length, mass per meter and EA are proposed. The water depth is reduced to 736 m and 552 m respectively, it is found their static characteristics are consistent with those of the original 913.5m system. The truncation method is proved to be valid.

2) To check two truncation methods in further step, coupled analysis of SPAR and its mooring system in full water depth and truncated depths are carried out in time domain. The 6-degree freedom motions agree well with model test results, while the mooring lines are underestimated because the quasi static method is used. Mooring tensions of two truncation designs are lower than un-truncated mooring tensions, but it is acceptable. As a whole, the truncation design is successful.

3) The simplification to risers is feasible and it has no influence on the static characteristics and global response of SPAR.

4) Research on dynamic characteristics of truncation mooring lines need to be investigated in future study.

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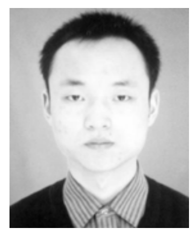

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