

DYNAMIC LOADINGS OF DEEPWATER SPAR PLATFORM – A CASE STUDY

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ABSTRACT

Various wave loadings are considered separately on the deepwater Spar platform, with the wave propagation along x-axis and dynamic analyses are carried out at 1150m water depth using Newmark- β approach. The dynamic responses along six degrees of freedom, i.e., surge, sway, heave, roll, pitch and yaw are analyzed. It is observed that responses due to sway, roll and yaw are negligible as compared to responses of surge, heave and pitch. Tensions at the mooring points are also presented in the paper.

INTRODUCTION

Many innovative floating structures have been proposed for the exploration of oil from the seabed. Spar Platform is one of such floating offshore structures used for deep water applications for drilling, production, processing, storage and offloading of ocean deposits. To reduce the wave induced motion, the natural frequency of these newly proposed offshore structures are designed to be far away from peak frequency of the force power spectra. The structure is made stable by maintaining the center of buoyancy above the center of gravity. Station-keeping is provided by the multi component catenary mooring lines attached to the hull near its center of pitch. Low motions and a protected center also provide an excellent configuration for the deepwater operations. The Spar can be operated upto 3000 m water depth, oil can be stored, risers are protected from inside the platform and it can have a large range of topside payloads. Many oil companies are considering Spar as the next generation of deep-water offshore structures.

Chen et al (2001) presented the dynamic coupling effects between the spar and the mooring lines for different water depths. Chitrapu et al (2001) made comparison on modal study of nonlinear response behavior of Spar considering slender theory and higher order theories. An Analysis of linear and nonlinear response behavior of Spar under regular waves and slender theory approach considered for wave kinematics, was presented by Agarwal and Jain (2003). Thiagarajan (2003) conducted a response study on classical spar; truss spar and cell spar, showing excellent behavior of cell spar in heave direction.

The main objectives of the present investigation are; i) to understand the response behavior of Spar for dynamic degrees of freedom and ii) to study the distribution of the tension in the mooring lines. Diffraction theory is considered for wave kinematics. Newmark- β method is used for dynamic analysis.

ESTIMATION OF DYNAMIC LOADINGS

Consider a linear plane wave traveling to the positive x-axis as shown in Fig 1. Here incident wave undergoes a significant scattering or diffraction upon arrival at the structure. The

motions of a floating structure in the six degrees of freedom also create disturbances in the fluid body, which is called the radiation effect. The boundary value problem for general diffraction theory assumes oscillatory incompressible and irrotational fluid motion for which the governing equation is the Laplace equation and the unknown quantity is the velocity potential.

The velocity potential (ϕ) is divided into incident potential, diffracted potential and radiated potential depending upon arrival to the structure. It satisfies the Laplace equation given in rectangular Cartesian coordinate system (oxyz) as

$$\nabla^2 \phi = (\partial^2 \phi / \partial x^2) + (\partial^2 \phi / \partial y^2) + (\partial^2 \phi / \partial z^2) = 0. \quad (1)$$

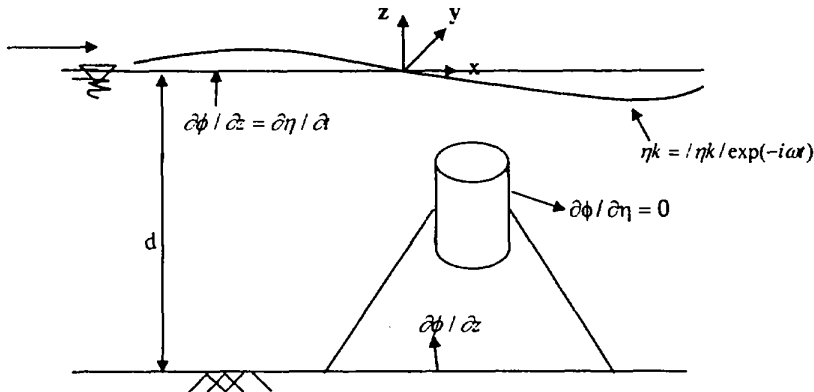


Fig.1. Boundary conditions for the linear diffraction problem

Once the value of the ϕ is known, we obtain the pressure of the fluid on the body from the Bernoulli's equation, for an inviscid fluid.

$$\partial \phi / \partial t + g z + 1/2 |\nabla^2 \phi| + P/\rho = F(t) \quad (2)$$

where ρ is the density of the fluid, P is the pressure, g is the acceleration due to gravity and $F(t)$ is a forcing function, constant in space, so we set its value to be zero. Considering the linear wave, we neglect the nonlinear term $|\nabla^2 \phi|$ as well.

Applying to Equation-(2)

$$P = -\rho \partial \phi / \partial t - \rho g z \quad (3a)$$

The force due to the pressure over the whole body is given by

$$F = - \int P_j n_j d s \quad (3b)$$

where, n is the normal vector normal into the field ; s is the surface area of the cylinder along horizontal plane at depth z and $j = 1$ to 6.

The following set of six linear coupled differential equations are written as,

$$\sum_{k=1}^6 [(M_{jk} + A_{jk})(\partial^2 nk / \partial t^2) + C'_{jk}(\partial nk / \partial t) + K'_{jk} \eta_k] = (F_j) \exp(-i\omega t) \quad (4)$$

where, $M_{jk} + A_{jk}$ = total mass coefficients in six degrees, C'_{jk} = Damping coefficients, K'_{jk} = Stiffness coefficients, F_j = Restoring force and $\eta_k = \text{surface elevation} / \exp(-i\omega t)$, surface elevation.

Assuming three major cases, i.e., surge, heave and pitch, Equation (4) can be written as

Surge Equation

$$[-(M_{11} + A_{11})\omega^2 - iB_{11}\omega + C_{11}]\eta_1 + [-A_{13}\omega^2 - iB_{13}\omega + C_{13}]\eta_3 + [-A_{15}\omega^2 - iB_{15}\omega + C_{15}]\eta_5 = F_1 \quad (5a)$$

Heave Equation

$$[-(M_{33} + A_{33})\omega^2 - iB_{33}\omega + C_{33}]\eta_3 + [-A_{31}\omega^2 - iB_{31}\omega + C_{31}]\eta_1 + [-A_{35}\omega^2 - iB_{35}\omega + C_{35}]\eta_5 = F_3 \quad (5b)$$

Pitch Equation

$$[-(M_{55} + A_{55})\omega^2 - iB_{55}\omega + C_{55}]\eta_5 + [-A_{51}\omega^2 - iB_{51}\omega + C_{51}]\eta_1 + [-A_{53}\omega^2 - iB_{53}\omega + C_{53}]\eta_3 = F_5 \quad (5c)$$

Using above three equations, three unknowns, viz, η_1 , η_3 and η_5 are solved for motions in surge, heave and pitch.

MOORING TENSION

The mooring tension is estimated from the following formula,

$$T = (L_1 - L_2) * E * A / L_2 \quad (6)$$

Where, E = Young's modulus of material; A = Area of the mooring line; L_2 = Unstretched length; L_1 = Stretched length

The Elastic stiffness, EA / L_2 when added to geometric stiffness, T / L_2 gives the final mooring stiffness.

STRUCTURAL CONFIGURATION

The Spar platform is modeled as a floating rigid cylinder (Fig-2) with six degrees of freedom (i.e. three displacements, i.e., surge, sway and heave, and three rotational, i.e., roll, pitch and yaw along X, Y and Z directions respectively) at its center of gravity (CG). The stability and stiffness is provided by a number of mooring lines attached near center of gravity for low dynamic positioning of the Spar platform. When the platform deflects, the movement takes place in the plane of symmetry of the mooring lines and the resultant force will also be acting in the same plane.

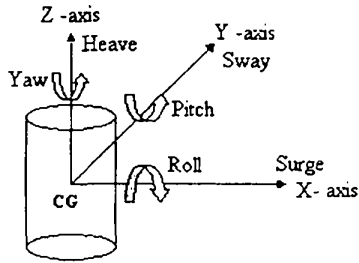


Fig 2. Degrees of freedom of a floating structure.

The details of Spar platform used in the present work are shown in Table-1 and Fig 3. The corresponding wave parameters for the load cases are extracted using PM Spectra for different wind speeds. The basic principle of floating body dynamics is that, if any wave comes and hits a structure, there will be a maximum displacement both along the direction of wave and vertical direction and an appreciable rotation along the adjacent axis of applied waves. Different wave loads are considered separately on the platform, with the wave propagation along x-axis and dynamic analyses are carried out using Newmark beta method.

Table 1 Spar dimensions and wave data

Diameter of Spar	32m
Length of Spar	180m
Depth of water	1150m
Mooring Lines	12 no.
Diameter of mooring	10cm
Center of gravity from top of platform	122m
Center of buoyancy from top of platform	100m
Angle between anchor point and fairlead	30 deg
Angle between the anchor lines	30 deg
Nature of waves applied	Regular waves
Platform weight	$1.7 \cdot 10^9$ N
Wave height	0.69 – 13.69m
Wave period	4.36-20.27 sec

MOTIONS OF SPAR PLATFORM

Table 2 shows the variation of responses due to wave loadings. It is observed that the response in the surge direction is maximum as the waves are applied along x-direction (Fig 4a) and it goes on reducing with the reduction of wave height. The heave response goes on reducing with decrease in

wave height (Fig-4b). It is also observed that the response along pitch is also decreasing with decrease in wave height (Fig 4c), and is maximum for 13.69m wave height. It is observed (Table-2) that the responses along sway, roll and yaw are very less as compared to that for surge, heave and pitch.

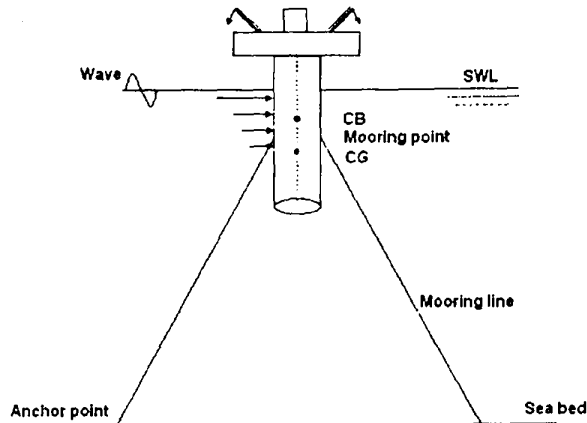


Fig. 3a Side view of Spar Platform

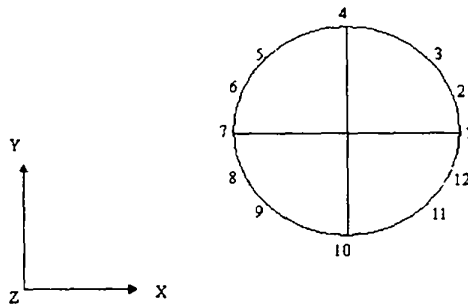


Fig. 3b Plan Showing Spar with all mooring points.

TENSION IN THE MOORING LINES

As waves approach the platform, all wave loads coming on it are transferred to the seabed through the mooring lines. The tension T at each fairlead point due to the mooring lines, in its initial position, is resolved into its three orthogonal components (T_x , T_y and T_z) in X , Y and Z directions. Variations of tension along the three directions, with wave height at each fairlead point are shown in Figures 5a to 5f.

Variation of tension at first and seventh fairlead points is shown in Fig.5a. Tensions at seventh fairlead points are slightly less than that in first point owing to structural

configuration and free-floating of large body. It is observed that Tx is maximum among all the mooring points. This is owing to wave loading being perpendicular to surface of the Spar platform at that point. Tx (1948 KN for first and 1860 KN for seventh mooring points) is maximum for 13.69m wave height, and reduces with the wave height. Ty is least among all the mooring points, and is perpendicular to x-axis. Tz (913 KN for first and 858 KN for seventh

mooring points) is less than Tx for maximum wave height of 13.69m.

This shows that horizontal load in x direction is prominent due to waves acting along that direction.

Table 2 Responses of the platform

Wave Height (m)	Surge (m)	Sway (m)	Heave (m)	Roll (deg)	Pitch (deg)	Yaw (deg)
13.692	6.430	0.0123	2.0300	2.377E-04	3.480	3.512E-02
13.015	5.660	0.0109	1.4400	1.73E-04	1.948	3.914E-02
12.350	5.001	0.0096	1.0400	1.174E-04	1.110	3.669E-02
11.714	4.410	0.0085	0.7520	7.276E-05	0.980	3.569E-02
11.090	3.900	0.0074	0.5450	3.781E-05	0.850	3.443E-02
10.483	3.440	0.0065	0.3950	2.395E-05	0.700	3.030E-02
9.892	3.040	0.0056	0.2840	3.810E-05	0.618	3.145E-02
9.319	2.680	0.0049	0.2030	5.609E-05	0.518	2.973E-02
8.763	2.360	0.0042	0.1440	7.105E-05	0.434	2.801E-02
8.223	2.070	0.0036	0.1000	8.193E-05	0.380	2.618E-02
7.701	1.810	0.0031	0.0690	8.995E-05	0.260	2.435E-02
7.196	1.580	0.0026	0.0470	9.453E-05	0.194	2.251E-02
6.709	1.370	0.0022	0.0317	9.683E-05	0.177	2.068E-02
6.238	1.180	0.0018	0.0213	9.683E-05	0.159	1.879E-02
5.784	1.020	0.0015	0.0143	9.453E-05	0.142	1.701E-02
5.348	0.867	0.0013	0.0098	9.653E-05	0.121	1.524E-02
4.929	0.743	0.0010	0.0069	8.537E-05	0.111	1.346E-02
4.527	0.615	0.829E-03	0.0052	7.907E-05	0.095	1.180E-02
4.141	0.509	0.661E-03	0.0038	7.220E-05	0.081	9.913E-03
3.773	0.415	0.520E-03	0.0028	6.417E-05	0.068	8.766E-03
3.423	0.333	0.401E-03	0.0021	5.575E-05	0.051	7.162E-03
3.089	0.260	0.301E-03	0.0015	4.710E-05	0.032	5.785E-03
2.473	0.145	0.154E-03	0.0006	2.990E-05	0.023	3.397E-03
2.190	0.101	0.103E-03	0.0004	2.220E-05	0.015	2.440E-03
1.925	0.068	0.653E-04	0.0002	1.535E-05	0.012	1.667E-03
1.676	0.043	0.390E-04	0.0001	1.008E-05	0.010	1.082E-03
1.445	0.026	0.220E-04	0.758E-04	6.245E-06	6.245E-03	6.858E-04
1.231	0.015	0.116E-04	0.389E-04	3.586E-06	3.598E-03	3.790E-04
1.034	0.007	0.569E-05	0.238E-04	2.022E-06	1.925E-03	2.030E-04
0.854	0.004	0.251E-05	0.254E-05	9.220E-07	9.224E-04	9.740E-04
0.691	0.001	0.710E-06	0.996E-06	2.830E-07	2.824E-04	2.985E-04

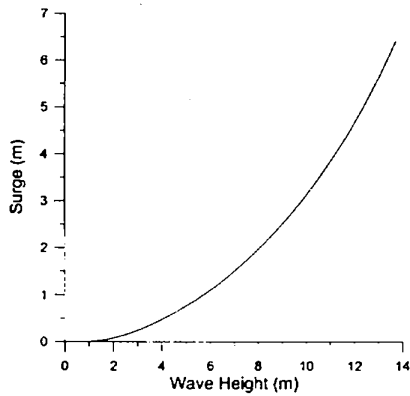


Fig.4a. Surge Response.

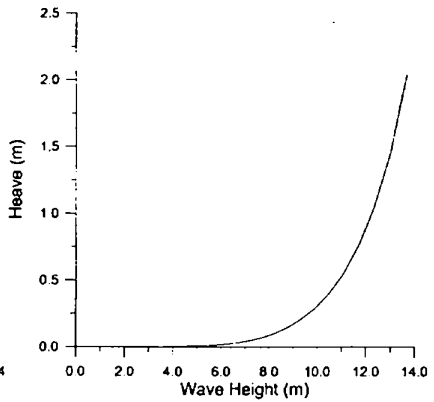


Fig.4b. Heave Response.

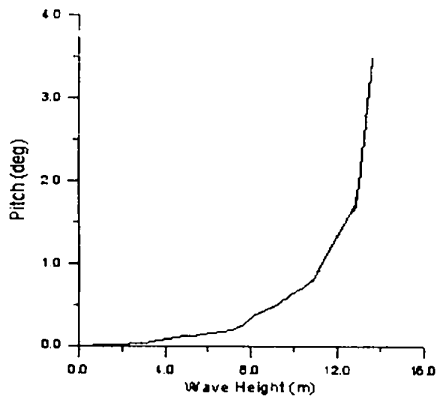


Fig.4c. Pitch Response

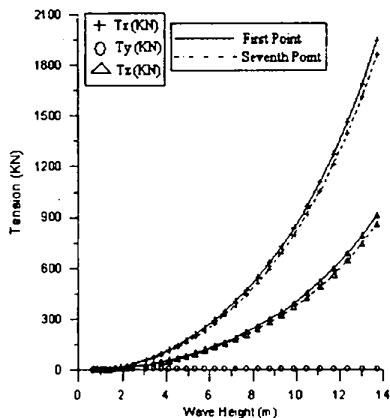


Fig.5a. Tensions in 1st and 7th mooring points

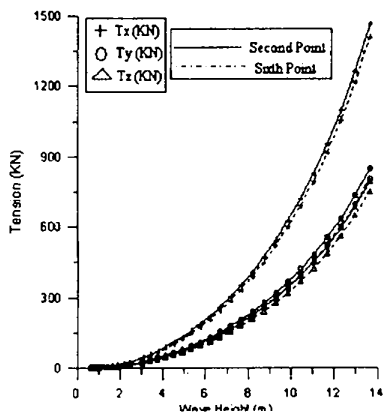


Fig.5b. Tensions in 2nd and 6th mooring points

Variation of tension in second and sixth mooring points in all three directions is shown in Fig 5b. It is observed that Tx (1460 kN for second and 1408 kN for sixth mooring points) is much larger than Ty (848 kN for second and 803 kN for sixth mooring points) and Tz (792 kN for second and 750 kN for sixth mooring points) for 13.69m wave height. The tension, Ty is larger than Tz and is much more than that at first mooring point as the wave front deviates from y-axis.

Fig 5c shows variation of tension in the third and fifth mooring points. It is observed that the tension, Ty (875 kN for third and 830 kN for fifth mooring points) is higher than Tx (504 kN for third and 492kN for fifth mooring points) and Tz (473 kN for third and 448kN for fifth mooring points) for 13.69m wave height as the wave front is approaching y-axis. The Tx and Tz are almost equal.

Fig 5d shows variation of tension in the fourth and tenth mooring point. It is found that the tension, Ty (305 kN for fourth and 308 kN for tenth mooring points) is dominating as compared to Tx and Tz, because the maximum force is acting on y-axis. The value of Tz (144 kN for fourth and 146 kN for tenth mooring points) is almost half the value of Ty.

Variation of tension at eighth and twelfth fairlead points, and ninth and eleventh mooring points are shown in Figs 5e and 5f respectively. All the three tension values of eighth and twelfth mooring points are almost equal to that of sixth and second mooring points due to symmetrical locations. Similarly the tension values of ninth and eleventh points are almost equal for fifth and third mooring points due to symmetry.

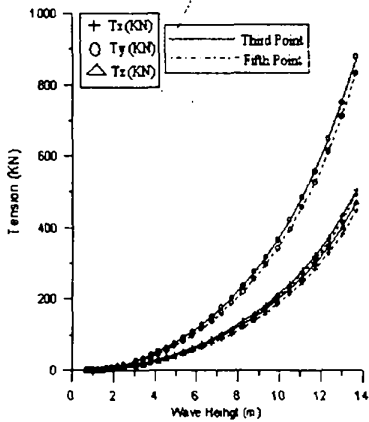


Fig.5c. Tensions in 3rd and 5th mooring points

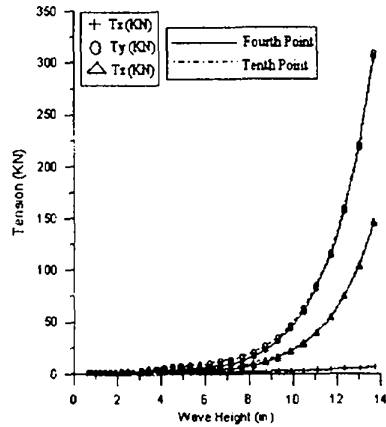


Fig.5d. Tensions in 4th and 10th mooring points

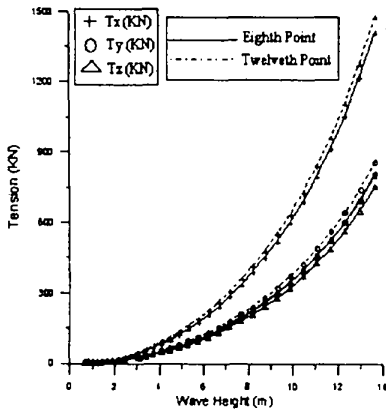


Fig.5e. Tensions in 8th and 12th mooring points

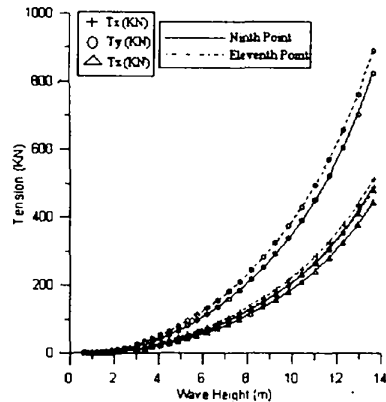


Fig.5f. Tensions in 9th and 11th mooring points

The maximum values of Tx, Ty and Tz are 1948, 887 and 913kN acting at the first, eleventh and first mooring points respectively for 13.69m wave height.

CONCLUSIONS

Based on the present study following conclusions are given below:

- The response in surge direction reduces with reduction in wave height.
- The responses in heave and pitch directions increase with increase in wave height.

- Tensions (T_x , T_y and T_z) in the mooring lines increase with the wave height.
- The maximum values of T_x , T_y and T_z are acting at the first, eleventh and first mooring points respectively.
- Tensions (T_x , T_y or T_z) of eighth and twelfth mooring points are almost equal to that for sixth and second mooring points, and tensions of ninth and eleventh points are almost equal to that of fifth and third mooring points due to symmetrical locations.

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