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Full Length Research Paper

Spar platform at deep water region in Malaysian sea

A. B. M. Saiful Islam*, Mohammed Jameel, Mohd Zamin Jumaat and S. M. Shirazi

Department of Civil Engineering, University of Malaya, Kuala Lumpur, Malaysia.

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Exploration of oil and gas resources has been accelerated towards deeper waters due to depletion of their reserve in shallow water depth. Malaysian sedimentary basins signpost the existence of these energy sources below its sea-bed. In deep sea depth, traditional fixed types of offshore structures to explore these resources have become incongruous and they have resorted to new configurations. Spar platform is treated as a cost-effective and efficient compliant floating platform in this locale for drilling, production, processing and storage of ocean deposits. This study deals with the oil and gas eminence in Malaysian sea along with structural response behaviors of spar platform subjected to hydrodynamic loading. A single model of spar-mooring line combination has been developed. Coupled conduct has been computed under unidirectional wave loading where all non-linearities are incorporated. Solution in time domain approach follows Newmark-beta integration technique. It is seen that the continental shelf offshore of Malaysian waters is divided into seven sedimentary basins, out of which three basins have major ongoing oil and gas exploration and production activity, namely the Malay basin in West Malaysia off Terengganu and the Sabah and Sarawak basins off the two East Malaysian states of Sabah and Sarawak, respectively. Surge, heave, pitch motion response of spar hull and tension in mooring line tension have been evaluated. Spar platform indicates itself as advanced and competent offshore structures to enhance the oil and gas exploration from all the Malaysian sedimentary basins in the deep water region.

Key words: Malaysian sea, deep water region, offshore structures, compliant floating, spar platform, hydrodynamic loading, mooring line, oil and gas resource, ocean deposit, sedimentary basin.

INTRODUCTION

Malaysia's first oil well was discovered on Canada Hill in Miri, Sarawak in 1910. Encouraged by the discovery of the Miri land field, there was no looking back as exploration and production activity stepped up and covered the entire Sarawak land mass, and followed by Sabah and Terengganu waters. To date, oil and later the discoveries of gas fields have propelled and fueled the socio-economic development of the country and its people for a number of eras. Oil and gas are the most widely used forms of energy that the world has ever known. The off-shore platforms are used for the exploration of oil and natural gas from sea-bed in addition to other uses. With the continuously increasing demand of petroleum, the need arises to explore the oil and gas reserves form deep water depths far off the continental shelf. In this region, conventional fixed jacket type off-shore platforms are highly uneconomical and proved to be unsuitable solutions. Alternative approaches for the exploration in deep sea conditions has resulted in development of series of flexible, compliant structures like the Tethered Buoy Tower (TBT), the Articulated Leg Platform (ALP), the Tension Leg Platform (TLP), etc. Spar platform is the latest among this new generation of compliant off-shore structures suitable for ocean drilling, production and storage of oil in deep water (Jameel, 2008; Islam et al., 2011a).

Malaysia has recently installed its first spar at Kikeh field near Sabah in 2007 (Kurian et al., 2008). It is the first spar in Malaysia located in more than 1000 m water depth offshore Sabah and is also the first one ever installed outside the Gulf of Mexico. The simple structure is characterized with a natural frequency far below the typical dominant ocean wave frequency-range aiming to

*Corresponding author. E-mail: abm.saiful@gmail.com. Tel: +60102573287. Fax: +60379675318.

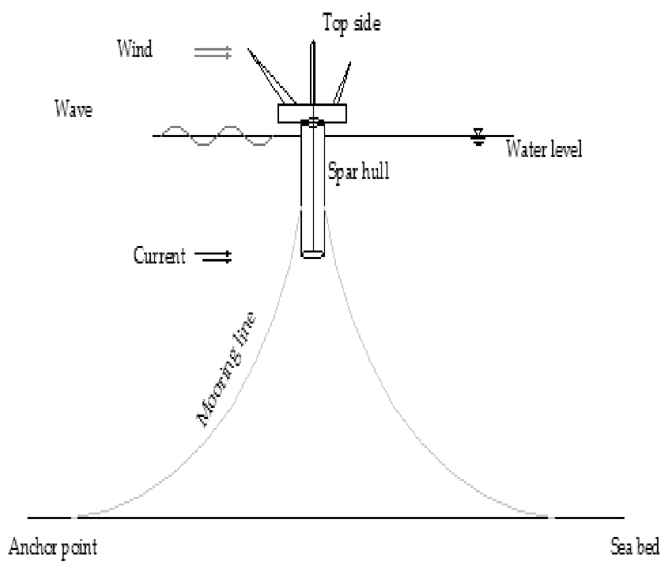

Figure 1. Configuration of Spar Platform.

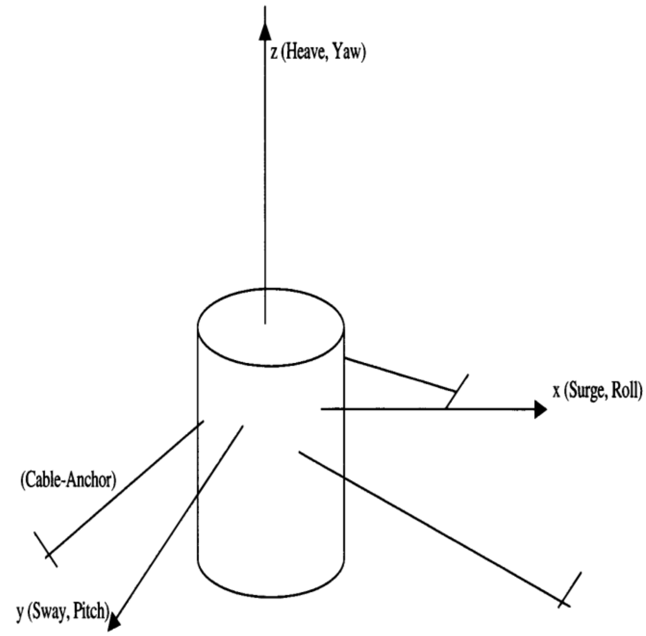

Figure 2. Spar and 6-degrees of freedom.

lessen the resulting dynamic effects. Appreciable reductions of wave-induced forced vibrations are stemmed in the range of frequencies of waves. In case of spar platform being installed in deep water, the riser and mooring lines contribute significant inertia and damping. Design of the mooring system/risers connected to spar platform hull are dominated by the motion of the spar platform (Figure 1). Accurate prediction of motions of spar platform is very important for the integrity and associated costs of the risers and mooring lines.

Numerous studies on spar platform are available in the literature (Ran et al., 1996; Ran and Kim, 1997; Ormberg and Larsen, 1998; Islam et al., 2011b). Chen and Zhang (1999) presented the response of a slack moored spar platform, to reveal the coupling effects between a spar and its mooring system. The responses were obtained by using a computer code COUPLE competent especially at deep water and it was compared with the corresponding laboratory measurements.

Ran et al. (1999) discussed non-linear coupled response of a moored spar platform in random waves both in time and frequency domains. It was observed that the time domain results, in general, produced larger wave frequency and slowly varying responses and mooring tension than the frequency domain results. Actual non-linearities of structures change its behavior a lot. However, consideration of significant non-linearities is very important for structural idealization (Jameel et al., 2011a; Islam et al., 2011c, d). Gupta et al. (2000) developed an analysis tool (ABASIM) to predict the dynamic response of platform, mooring lines and risers. The program combined ABAQUS and MLTSIM. The results indicated that the damping induced by mooring line drag and riser friction could explain the very low levels of heave response during Hurricane Georges. When the additional damping in heave response was included, the draft of the spar was reduced.

Ma and Patel (2001) examined the hydrodynamic interaction of spar platform with ocean waves and the quantification of those non-linear wave components. The results demonstrated that the centrifugal and axial divergence force components could be significant, as compared to those of the non-linear force due to wave acceleration. Chen et al. (2001) carried out the response of spar platform constrained by slack mooring lines. The dynamics of the spar and the mooring system were simulated using two different numerical schemes; a quasi-static approach and a coupled dynamic approach. In the quasi-static approach, the mooring system was modeled as mass-less non-linear spring. In the coupled dynamic approach the dynamics of mooring system was obtained using a numerical code CABLE 3D. The equations of motion for spar and its mooring lines were solved simultaneously in time domain, by matching the displacements and forces of the mooring lines with the Spar at fair leads. It was found that the damping of mooring lines reduced the slow drift surge (10%) and pitch motions of the spar platform. The mooring line tension in the wave frequency range predicted by coupled dynamic approach was eight times more than the corresponding prediction by the quasi static approach for the same water depth.

Anam (2000) has done the dynamic response analysis of spar platform. Figure 2 idealize the response direction

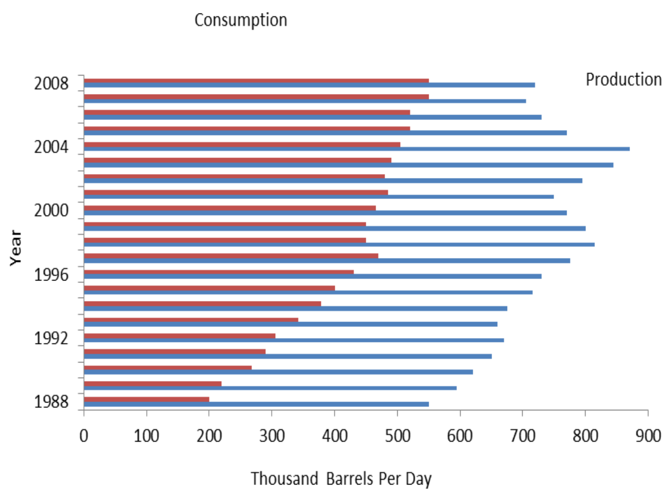

Figure 3. Malaysian oil production and consumption.

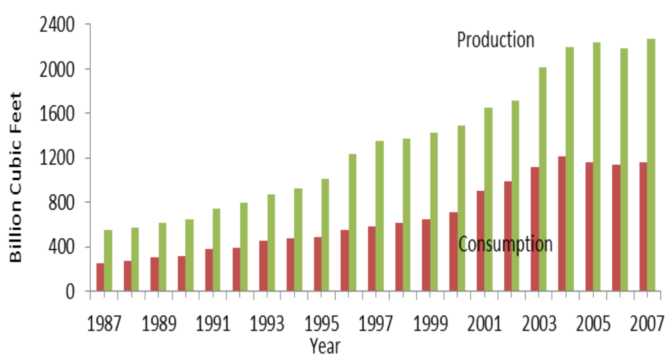

Figure 4. Malaysian natural gas production and consumption.

in the study. Anam et al. (2003) studied time domain and frequency domain analysis of spar platforms.

Chernetsov and Karlins (2006) proposed floating sub-structures for Stockman gas field in North West Russia. The three proposed sub-structures were Spar-Classic, Spar-Ring and tension leg platform (TLP)-Ring. Under ice pressure the spar and Semi-submersible substructures were found to be unsuitable due to their intolerable flexibility. Therefore, the SPAR-Ring was shown as the most adaptable floating structure for construction.

Tahar and Kim (2008) developed numerical tool for coupled analysis of deep water floating platform with polyester mooring lines. Low and Langley (2008) presented a hybrid time/frequency domain approach for coupled analysis of vessel/mooring/riser. The vessel was modeled as a rigid body with six degrees-of-freedom, and the lines were discretized as lumped masses connected by linear extensional and rotational springs. The method was found to be in good agreement with fully coupled time domain analysis, when used for relatively shallow water depths. Low (2008) used the same hybrid method to predict the extreme responses of coupled floating structure.

Jameel (2008) investigated fully coupled integrated spar-mooring line system. The large spar cylinder was physically linked with mooring lines at fairleads provided by six non-linear springs. The commercial finite element code ABAQUS/AQUA was used to model the configuration. Modeled spar-mooring system has been analyzed in effect of proper environmental loading at regular wave. The structural response behavior have been evaluated in the form of surge, heave, pitch motion and mooring line tension. Islam et al. (2011a) have developed the fully coupled integrated model of spar-mooring system and compared the wave hitting effect at 1000 to 2000 s and 6000 to 7000 s. Jameel et al. (2011b) have performed similar study but for longer duration of time state after storm. Mooring line can causes significant tension even after long time relaxation of wave hitting on spar platform.

Although, a great deal of research has been carried out regarding offshore compliant floating spar platform, there is a lack of more research for competent configuration on the spar platform around. The hydrodynamic loading pattern acting on the structures needed to be explored more. The combined structural effects of spar, mooring lines and risers are required to be included more precisely. The existing modeling treated the configurations to be some sorts of arbitrary element type under assumption. So, the objective of this study is to explore the oil and gas eminence in Malaysian sea along with structural response behaviors of coupled integrated spar platform subjected to hydrodynamic loading.

OIL AND GAS RESOURCES IN MALAYSIAN SEA

The offshore lands in Malaysia are a great source of oil and natural gas energy. It explores lot of these types of ocean deposits to cover the present need of energies. The production of oil and gas is beyond the consumption of its own. Therefore, Malaysia is a significant net exporter of oil and the second largest exporter (EIA, 2009) of liquefied natural gas (LNG) in the world behind Qatar. Malaysia also holds proven oil reserves as much as 4 billion barrels and gas reserves as much as 83 trillion cubic feet as of January 2009. Nearly all of Malaysia's oil and gas comes from offshore fields.

As exemplified in Figures 3 and 4, Malaysia’s oil and gas production (EIA, 2010) has seen a steady growth over the past 20 years, more so for LNG which has become a major export commodity for the country, at 2.3 trillion cubic feet (cu. ft.) in 2007. As of 2008, Malaysia’s oil production was reported to be 727,000 barrels per day (bbl/day). Partly driven by the ever increasing demands for energy worldwide and new technological breakthroughs, the industry continues to flourish as new fields are discovered and brought into production faster and with improved oil recovery.

Malaysian sedimentary basins are major areas for potential oil and gas reservoirs as they contain many faults and natural traps, which collects and accumulate hydrocarbons under its impermeable layer. As shown in Figure 5, the continental shelf offshore of Malaysian waters is divided into 7 sedimentary basins, out of which 3 basins (Madon, 1999) have major ongoing oil and gas exploration and production activity, namely the Malay basin in West Malaysia off Terengganu and the Sarawak and Sabah basins off the two East Malaysian states of Sabah and Sarawak. Most of the country’s oil reserves are located in the Malay basin and tend to be of high quality. Malaysia’s benchmark crude oil, Tapis Blend, is very light and sweet with an American Petroleum Institute (API) gravity of 44° and sulfur content of 0.08% by weight. More than half of the total Malaysian oil production comes from the Tapis field.

Since 2002, the focus has been on deepwater fields on the eastern continental shelf that pose high operating costs and require substantial technical expertise. New oil production projects in the planning or construction phase include: The Gumusut/Kakap project, located offshore Sabah in 3,937 feet (1200 m) of deep water, will include the regions' first deepwater floating production system with a processing capacity of 150,000 bbl/day from 19 subsea wells.

As the oil and gas industry looks further into newer ways and locations to recover hydrocarbons, exploration and production activity has seen itself heading towards greater frontiers. In other words, deeper and deeper wells are being drilled and completed, this in turn results in greater challenges for designing and setting up of offshore production facilities. Table 1 shows the timeline of operation for the deepwater projects in Malaysia, and it can be seen that Malaysia is already priming itself to be a deepwater operations regional hub.

SPAR PLATFORM FOR MALAYSIAN SEA

The design and operation of off-shore structures evolved out of extensive theoretical analysis, model testing and practical experience in the scientific disciplines that lead to the exploitation of oil and gas reserves from hydrocarbon reservoirs below the seabed. For the deep-water operations, the older conventional fixed and bottom supported complaint platform are not suitable, and therefore, several innovative floating platform design concepts, such as: drill ships, semi-submersibles, spar platforms, floating towers, floating jacket and deep draft caisson vessel have been proposed. Spar platform is the latest and most efficient compliant floating structure. This floating platform is becoming increasingly attractive, because of some additional advantages. It can be mobile and used repeatedly, especially in the case of reservoirs with marginal reserves. The lag time from discovery to

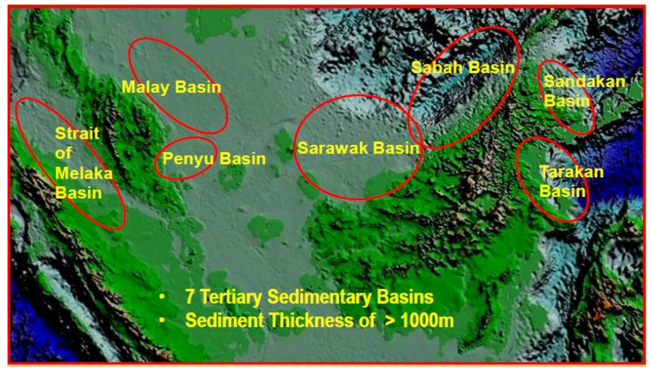

Figure 5. Sedimentary basins of Malaysia.

first production can be reduced. It can be quickly disconnected permitting passage for extreme conditions, large ice bergs and in addition, its design may not be significantly affected by the earthquake and water depth.

Spar platform consists of a vertical cylinder, which floats vertically in water. The structure floats so deep in water that the wave action at the surface is dampened by the counter balance effect of the net buoyancy of the structure. Station keeping is provided by lateral, multi-component catenary anchor lines attached to the hull near its center of pitch for low dynamic loading (Figure 1). The hull of the classic (full cylinder) spar consists of three main sections, namely, the upper buoyant, hard tank section, the flooded mid section which can be configured for oil storage on top of a water cushion and the flooded soft tank section at the keel. Rigid steel production risers are located within the moon pool where the protected water allows each riser to be supported in tension by its own buoyancy module. Although, spar’s lateral motions in the extreme storms are quite limited, usually 4 to 8% of the water depth, the riser does experience noticeable bending at the keel of the vessel and at the seafloor wellhead due to lateral motions. The sea floor end of each mooring line is anchored with a driven pile or suction pile while the hull end passes through a fairlead located well below the water surface, then extending up the outside of the hull to chain jacks at the top. The topside configuration follows typical fixed platform design practices. The decks can accommodate a full drilling rig or a work-over rig plus full production equipment.

Using the basic idea for the spar hull, mooring system, topsides, production risers and export risers, a spar platform can be configured in various ways including production only, or any combination of production, work-over and drilling. This spar-mooring system has been modeled in single integrated coupled continuum.

STRUCTURAL MODELING

Spar hull and mooring line coupled action has been

Table 1. List of deepwater fields that are in appraisal/operation.

Field name	Recoverable	Water depth (m)	Onstream date	Operator
Kikeh	536 mmboe	1,300	Q2/Q3 2007	Murphy oil
Gumusut/Kakap	620 mmboe	1,220	Q4 2010/Q1 2011	Shell
Kebabangan	2.2 tscf	>200	Q3 2011	Conoco P.
Jangas	81 mmboe	>1000	Q4 2011	Murphy oil
Ubah Crest	215 mmboe	>1000	Q2 2012	Shell
Pisangan	56 mmboe	>1000	Q3 2012	Shell
Kamunsu	2.2 tscf	>1000	Q2 2013	Shell

captured with required structural and environmental non-linearities. Water particle kinematics estimates the drag and inertia for all the six degrees of freedom. The static coupled problem is solved by Newton's method. In order to incorporate high degrees of non-linearities, an iterative time domain Newmark-β time integration scheme has been adopted for solving the coupled dynamic model. The equation of motion describing the spar-mooring system equilibrium between inertia, damping, restoring and exciting forces can be assembled as follows:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \qquad (1)$$

Where [M], [C] and [K] are the total mass, damping and stiffness matrices, respectively of the spar-mooring system. The 6 degrees of freedom (DOF) structural displacements are represented by {X} and the dot denotes differentiation with respect to time. The total spar-mooring mass matrix of the system consists of structural mass and added mass components. The structural mass of the Spar-mooring system is made up of elemental consistent mass matrices of the moorings and lumped mass properties of the rigid Spar hull. The lumped mass properties are assumed to be concentrated at the centre of gravity (CG) of spar hull. The added mass of the structure occurs due to the water surrounding the entire structure. The total stiffness matrix element [K] consists of two parts, the elastic stiffness matrix [K_E] and the geometrical stiffness matrix [K_G]. The overall damping to the system is being offered by structural and hydrodynamic damping. The major damping is induced due to the hydrodynamic effects. The structural damping is simulated by Rayleigh damping.

The investigation of spar platform considering actual physical coupling between the rigid vertical floating hull and mooring lines is performed in finite element model. This model can handle all non-linearities, loading and boundary conditions. The commercial finite element code ABAQUS/AQUA has been utilized for the present analysis. It is capable of simulating the hydrodynamic loading due to wave. The equation of motion (Equation 1) has been solved using this finite element code.

The spar hull is modeled as an assemblage of rigid beam elements connecting its center of gravity, riser reaction points and mooring line fair leads. The radii of gyration and the cylinder mass are defined at CG. The rigid spar platform has been connected to the elastic mooring lines by means of six springs (Three for translation and three for rotation). The stiffness's of translation springs are very high, whereas the stiffness's of rotational springs are very low simulating a hinge connection.

Hybrid beam element is used to model the mooring lines. It is hybrid, because it employs the mixed formulation involving six displacements and axial tension as nodal degrees of freedom. The axial tension maintains the catenary shape of the mooring line. The element under consideration experiences the wave forces due to Morison's equation. The self-weight and axial tension are duly incorporated. [K_G] models the large deformation associated with mooring configuration. Hydrodynamic damping is dominant in case of oscillating slender member surrounded by water.

CASE STUDY

The spar-mooring line system is analyzed allowing elemental coupling effect under regular ocean wave. For the case study to incorporate the spar platform model in deep Malaysian sea, the water depth has been chosen as 1018 m. Significant Wave height is considered as 6 m and wave period equals 14 s. The mechanical and geotechnical properties of the spar-mooring system under study are given in Table 2. Table 3 illustrates the hydrodynamic individualities of sea environment. When the wave forces act on the entire structure, participation of mooring lines in the overall response is well depicted. Through the time domain analysis using step-by-step integration procedure, the response time histories are obtained for sufficient length of time so that the response attains their steady state. The analysis of spar-mooring system for deep water condition has been performed up to 3600 s. To understand the mooring damping and coupling effect, the conducts have been plotted in two sets for each response. The statistical characteristics of the spar responses is also determined taking these time lengths.

Table 2. Mechanical and geometrical properties of spar-mooring system.

Element	Property	
Spar (Classic JIP Spar)	Length	213.04 m
	Diameter	40.54 m
	Draft	198.12 m
	Mass	2.515E8 kg
	Mooring point	106.62 m
	Number of nodes	17
	Number of elements	16
	Type of element	Rigid beam element
Sea-bed	Size	$8000 \times 8000\ m^2$
Sea water	Depth	1018 m
Mooring	Number of moorings	4
	Stiffness (EA)	1.501E9 N
	Length	2000.00 m
	Mass	1100 Kg/m
	Mooring line pre-tension	1.625E7 N
	Number of nodes	101
	Element type	Hybrid beam element

Table 3. Hydrodynamic properties.

Structural element	Hydrodynamic coefficient	
Spar hull	Drag coefficient	0.6
	Inertia coefficient	2.0
	Added mass coefficient	1.0
Catenary mooring line	Drag coefficient	1.0
	Inertia coefficient	2.2
	Added mass coefficient	1.2

Excursion of spar platform

The computational efforts required for the coupled analysis considering a complete model including all mooring lines are substantial. The ability for more accurate prediction of platform motions by coupled analysis approach may consequently contribute to a smaller and less expensive spar-mooring. The results are shown in Figures 6 to 10. All the time series are presented through these figures. In addition, free vibration analysis and statistical analysis in forms of maxima, minima, mean and standard deviation has also been exposed in Tables 4 and 5, correspondingly.

Surge motion excursion

The behavior of surge motion in terms of time series is shown in Figure 6 for the position of the deck level. The peak of surge response ranges from +19.253 to -17.962 m (Table 4). The surge motion at the deck level is predominantly periodic. The pitch motion (Figure 8) occurs concurrently with surge and appeals substantial wave energy close to the pitch frequency. Surge response requires huge energy input because of large inertia and hence, do not get excited. However, pitching motion occurring with surge gets excited easily. The excursion of surge at the deck level is mainly dominated by the pitching motion of the spar hull with minor excitation of surge mode. It is mainly due to coupling of surge and pitch. Consequence of non-linearity is not very sturdy on surge motion excursion.

Heave motion excursion

The excursion of heave motion directly inspires the mooring

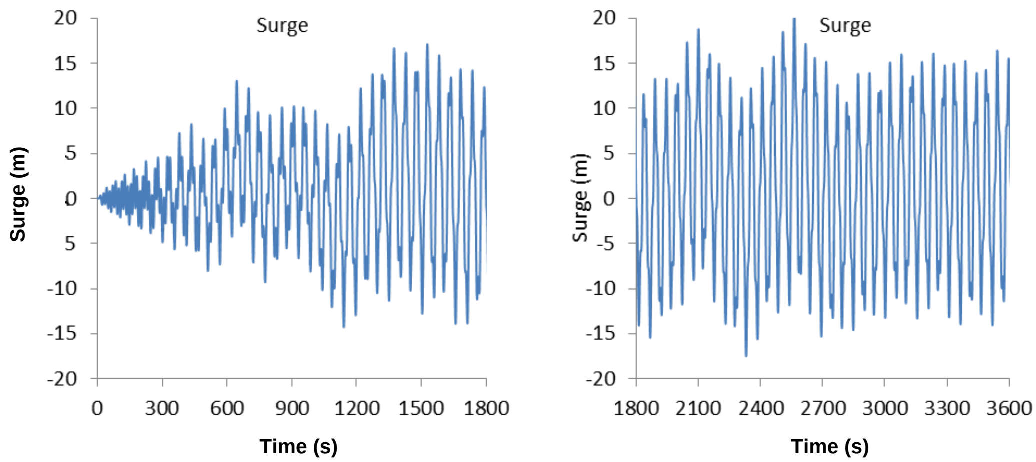

Figure 6. Surge motion excursion.

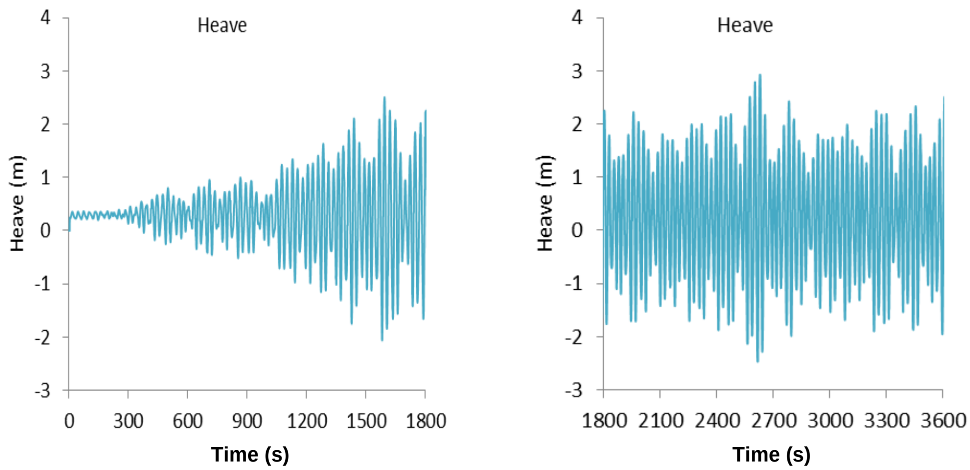

Figure 7. Heave motion excursion.

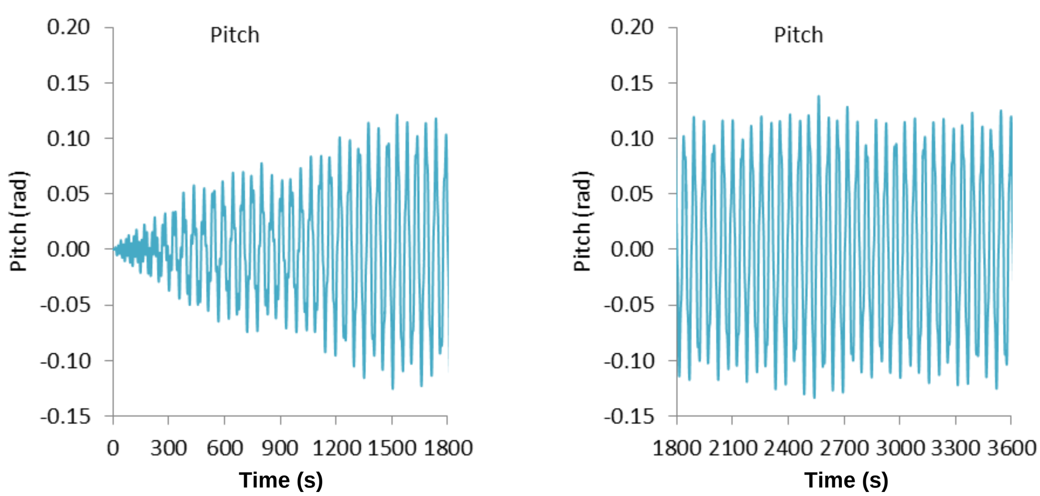

Figure 8. Pitch motion excursion.

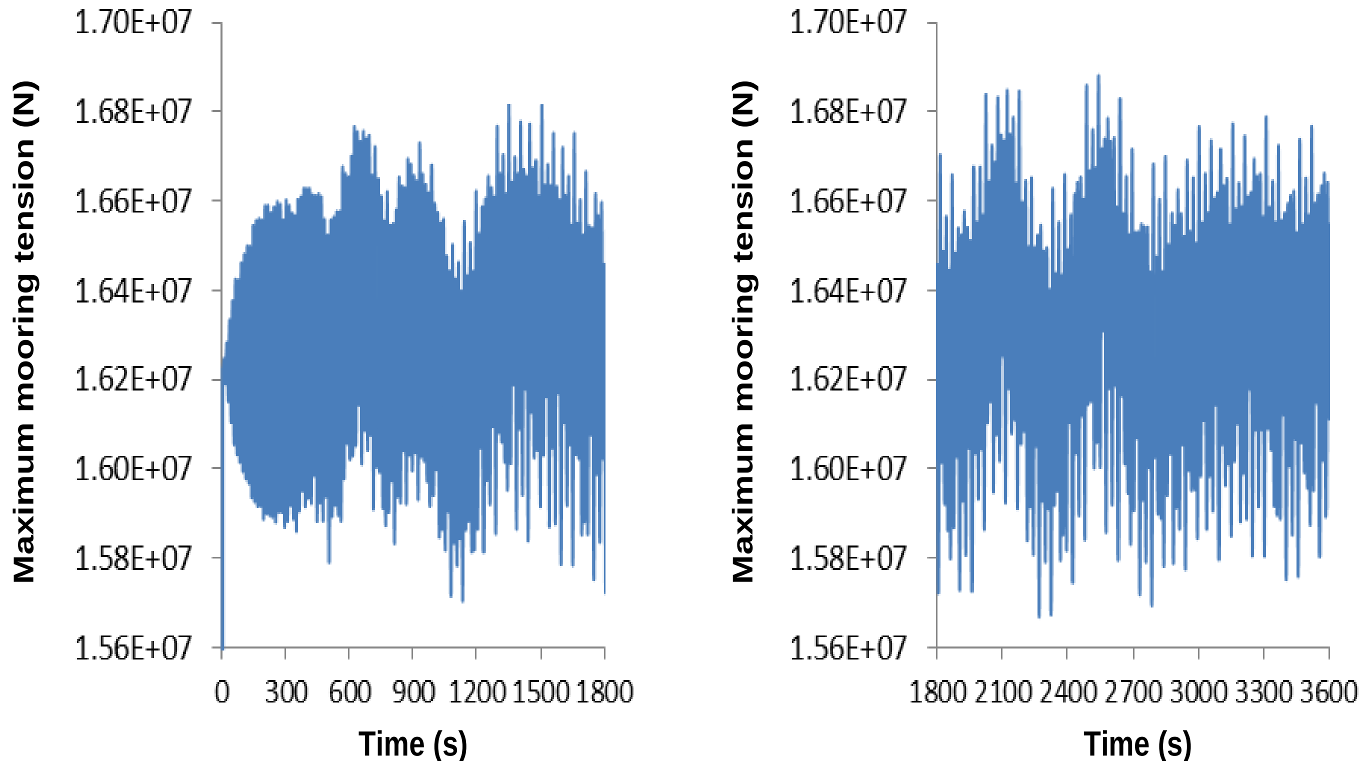

Figure 9. Tension in mooring line prior to structure at wave direction.

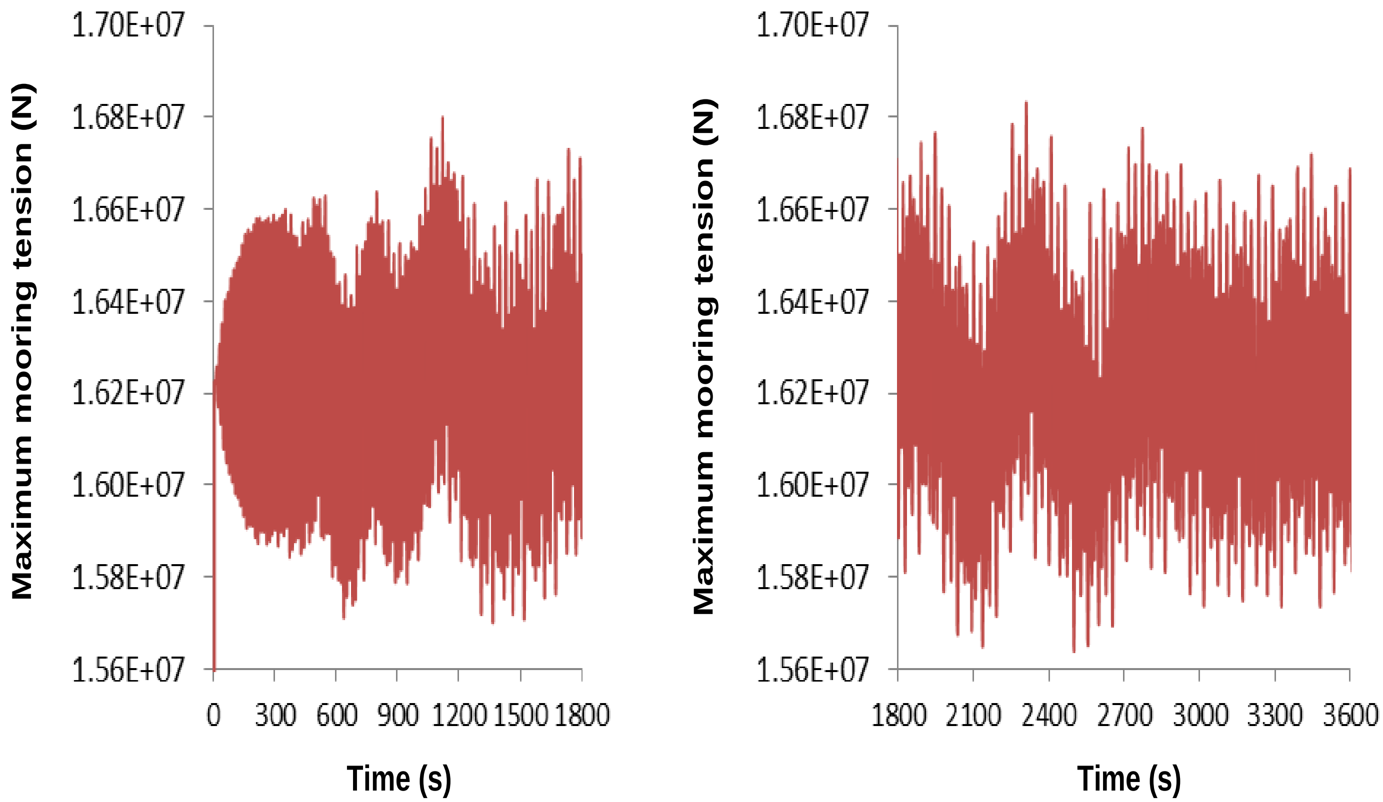

Figure 10. Tension in mooring line next to structure at wave direction.

Table 4. Natural frequencies for first 8 modes in free vibration analysis.

Excursion	Maxima	Minima	Mean	Standard deviation
Surge (m)	19.253	-17.962	1.132	9.221
Heave m)	3.010	-2.713	0.415	1.253
Pitch (rad.)	0.136	-0.139	0.0001	0.082
Tension in Mooring line 1 (N)	1.688E7	1.567E7	1.628E7	2.753E5
Tension in Mooring line 3 (N)	1.683E7	1.563E7	1.624E7	2.687E5

tensions and other operations. The heave responses under unidirectional regular wave are as shown in Figure 7. The time histories show the cluster of reversals occurring at varying time intervals. The pattern shows the regularity in the behavior. The statistical Table 5 displays the maximum and minimum responses as 3.010 and -1.981 m in magnitude, while the mean value leads to 0.415. Heave response fluctuates about the mean position oscillating from smaller to larger amplitudes and repeating the same trend onwards all through the time series. The fluctuations gradually increase from narrow to broad and after each peak, it gradually reduces by 25 %.

Pitch motion excursion

Figure 8 illustrates the pitch motion behavior up to 3600 s time period. The time series confirms regular fluctuations in lower time state, increase for a while and again the peaks are decreased. This trend continues in consistent manner. At 2670 s, the maximum peaks occur. The statistical Table 5 that shows the maximum positive and negative pitch values of +0.136 and -0.139 rad. The mean value is almost zero and the standard deviation is 0.082 rad. The mean value of zero shows its regular oscillations about the mean position. The momentous value of pitch response leads to a significant surge at deck level. It is coupled with the surge of rigid hull which otherwise is of small magnitude but gets enhanced due to pitch input.

Mooring line tension response

Tension in mooring lines plays an imperative character in the coupled dynamic analysis of the spar platform. The designed pretension in each mooring line of the present problem is 1.625E7 N (Table 1). Mooring line 1 shows the regular behavior of tension in direction of wave propagation (Figure 9). The statistics show the maximum and minimum values as 1.688E7 and 1.567E7 N, respectively in mooring line 1. The tension time series of mooring line 3 is likewise regular in nature (Figure 10). It is important from fatigue view point. However, there is slight fluctuation in magnitude. Mooring line 3 is positioned in the direction of wave propagation too. Mooring line 1 experiences the maximum tension to support surge in the forward direction, while mooring line 3 slackens, resulting in the reduction of pretension. Figures 9 and 10 show the tension fluctuations when mooring line 1 stretches and mooring line 3 slackens due to surge response. Tension fluctuation is of complex periodic nature showing minor ripples near the peaks. For both of these mooring lines at the regular wave, periodic behavior is governed. The slack mooring line 3 remains in catenary shape with the reduction in tension. Maximum tension in mooring line is damped out progressively with increase of wave hitting time relaxation.

Conclusion

This paper gives a detail assessment on oil and gas resources in Malaysian sea. It is seen that the continental shelf offshore of Malaysian waters is divided into 7 sedimentary basins, out of which 3 basins have major ongoing oil and gas exploration and production activity, namely the Malay basin in West Malaysia off Terengganu and the Sabah and Sarawak basins off the two East Malaysian states of Sabah and Sarawak, respectively. First and only one spar platform has been installed recently at Kikeh field. The technical development of spar platform, including the research on dynamic responses, mooring systems and coupling phenomena of its own has been assessed. A single model of spar-mooring line combination is developed. Surge, heave, pitch motion excursion of spar hull and mooring line tension have been evaluated. Spar platform indicates itself as advanced and competent offshore structures to enhance the oil and gas exploration from all the Malaysian sedimentary basins in deeper water depth.

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