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Hydrodynamic Response of Spar with Single and Double Heave Plates in Regular Waves

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Abstract

The motion response of floating structures should be adequately low to permit the operation of rigid risers along with dry well heads. Though Spar platforms have low heave responses under lower sea state, could become unacceptable in near resonance region of wave periods. Hence the hydrodynamic response, heave in particular, must be examined to ensure that it is minimized. To reduce heave motions, external damping devices are introduced and one such effective damping device is heave plate. Addition of heave plate can provide additional viscous damping and additional added mass in the heave direction which influence the heave motion. The present study focuses on the influence of heave plate on the hydrodynamic responses of Classic Spar in regular waves. The experimental investigation has been carried out on a 1:100 scale model of Spar with single and double heave plates in regular waves. Numerical investigation has been carried out to derive the hydrodynamic responses using ANSYS AQWA. The experimental results were compared with those obtained from numerical simulation and found to be in good agreement. The influence of disk diameter ratio, wave steepness, pretension in the mooring line and relative spacing between the plates on the hydrodynamic responses of Spar are evaluated and presented.

Keywords: Spar; Single and double heave plate; Viscous damping; Added mass; Vortex shedding; Hydrodynamic response; motions; mooring line tension.

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1. Introduction

As offshore oil and gas exploration moves into deep water, many innovative floating systems are being proposed for cost saving and optimum performance. Spar hulls are deep draft floating system used for drilling, production, processing, storage and offloading. So far many classic and truss Spars have been installed in the past. Though variety of configurations has been investigated in the past, classic and truss Spars are prominent in the oil and gas industry. The basic configuration usually referred to as the classic Spar comprises of a floating deep draught cylindrical caisson. It consists of “hard tank” near the top to provide buoyancy and there is a flooded skirt below the upper buoyant section. The lower section consists of “soft tank” which can be used for holding variable sea water ballast. The Spar platforms generally have a heave natural period in the range of 20 to 30 sec. As the heave natural period of the Spar is sufficiently outside the prevailing wave frequency range, it has distinct advantage of reduced heave motion. This helps in a use of dry trees and rigid risers. It has also provision for storage of substantial quantity of crude oil in its hull. Therefore the classic Spar provides an attractive design solution for regions where the environment is harsh as well as in the regions were crude oil storage is required.

However, the classic Spar possesses low damping and long natural period. These two characteristics, together with long period swell, may produce linearly

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excited heave resonant motion of the Spar up to 8 to 10 times of incident wave amplitude. These large amplitude heave oscillations may cause damage to both risers and mooring systems. Hence the hydrodynamic response optimization, especially heave, is an important issue which needs to be addressed for efficient operation.

The heave response of the Spar depends on wave excitation forces, natural period of the system and hydrodynamic damping. The heave natural period ($T_{N,3}$) of classic Spar can be calculated using the formula given below.

$$T_{N3} = 2\pi\sqrt{\frac{M + A_{33}}{\rho g A_W}} \qquad (1)$$

where M and A_{33} represent mass and added mass of the Spar, Aw is the area of water plane, ρ is the density of water and g is the acceleration due to gravity. The equation (1) indicates that the heave natural period can be increased by increasing the draft, mass and added mass of the system or decreasing the water plane area. However, increasing the draft and consequently increasing the system mass leads to many other considerations in the design along with cost of construction, transport and installation. Hence, increasing the heave natural period is not a viable economic solution.

In addition to increasing the heave natural period of a Spar beyond the dominant wave energy range, increasing heave damping is another efficient means of reducing the heave response. The motions of floating bodies are usually damped by a combination of wave radiation and viscous damping in the form of skin friction and flow separation. As a means of imposing viscous damping, additional active damping systems are introduced externally. A typical example of this damping system is a heave plate which is attached to the keel of the Spar (Fig. 1).The addition of heave plate at the bottom of the Spar increases heave added mass and damping, which results in longer heave natural period (Eq. (1)) as well as reduced motion due to higher damping.

2. Literature Review

Many researchers have investigated the hydrodynamic response of Spar and the various methods to control them. Thiagarajan and Troesch (1998) conducted model tests to examine the effect of adding an appendage in the form of disk to Tension Leg Platform columns and the influence of a small uniform current. The disk was found to increase the form drag coefficient (C_d) two fold. It was also found that the heave damping ratio of a cylinder increases linearly with current velocity. Fischer and Gopalkrishnan (1998) presented the importance of heave characteristics of Spar platforms that have been gleaned from wave basin model tests, numerical simulations and combination of the two. It was concluded that the optimum spacing between the heave plates is approximately one cylinder diameter which is based upon only from damping coefficient obtained from free decay tests. Haslum and Faltinsen (1999) proposed that the wave frequency heave resonant response might be reduced in three ways: (a) Increasing the damping of the system; (b) Increasing the natural heave period out of range of wave energy; and (c) Further reducing the linear heave excitation forces through alternative hull shapes. They studied the hydrodynamic responses of alternative shape of Spar platforms using a simplified calculation method. It was concluded that alternative hull shapes improved the heave and pitch motion characteristics. Rho *et al.* (2002) carried out an experimental study on heave and pitch motions of various Spar configurations with a model scale of 1:400 and investigated the effect of moon pool, strakes and damping plate. It was concluded that, spiral strake and the damping plate are effective in reducing the resonant heave motions by about 25% and 50% respectively. Also Mathieu instability which occurs when the period of incident wave is equal to the heave natural period and half of the pitch natural period. Tao *et al.* (2004) investigated the hydrodynamics of heaving vertical cylinder with a single disk attached at the keel. It was found that the aspect ratio of the disk t_d/D_d was found to have the most striking effect on vortex shedding and the viscous damping, while disk diameter ratio D_d/D_s was found to have significant impact on added mass. Numerical experiments showed that the disk extension should be at least four times typical heave amplitude to achieve the optimum drag effect. Hong *et al.* (2005) carried out model tests on four types of Spar models in order to understand the influence of heave augmentation devices on response characteristics. The positive effects of strake and heave damping plates were confirmed. Tao *et al.* (2007) carried out numerical simulations using finite difference approach to investigate the effect of relative spacing (L_d/D_d) on added mass and damping coefficients in a heaving vertical cylinder attached with two circular disks. It was concluded that the disk should be placed in the L_d/D_d independent region in order to achieve the maximum benefit of motion suppression due to increased damping. Sudhakar and Nallayarasu (2011) conducted experimental and numerical investigation on the heave response of classic Spar with circular heave plates of different diameter in regular waves. It was recommended that the diameter of the heave plate in between 20% to 30% larger than the diameter of the Spar reduces the heave, surge and pitch responses to an optimum value. Nimmy et *al.* (2012) carried out numerical simulation of the flow around circular disks of three different configurations, attached to a Spar buoy. In addition to the numerical simulation, flow visualisation and measurement using Particle Image Velocimetry (PIV) has also been carried out for comparison and evaluation. It was concluded that the added mass was found to be maximum for the Spar with double disk, thereby reducing the excitation force, making the system more stable in heave.

It can be observed that very few experimental studies have been reported in the literature. Hence, a detailed experimental investigation has been carried out on damping characteristics and hydrodynamic responses of Spar hull by varying the diameter of the heave plate and relative spacing between the heave plates. The numerical model is also validated with experimental results for specific cases. Recommendations on the diameter of the heave plate and spacing between the heave plates are made based upon experimental results. This can be effectively used for the improved design of floating platforms such as Classic Spar.

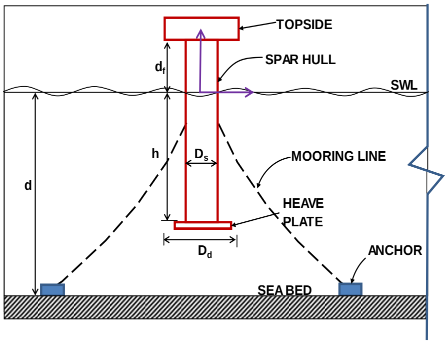


Fig. 1. Classic Spar with heave plate

3. Objective and Scope

The objective of the present study is to investigate the influence of single and double heave plates on the hydrodynamic response of Spar hull in regular waves. The detailed scope of the study is summarized below:

- Experimental studies to measure hydrodynamic responses of a Spar with single heave plate in regular waves.
- Experimental investigation to measure hydrodynamic responses of a Spar with double heave plates in regular waves.
- Numerical simulation of hydrodynamic responses of Spar with single and double heave plates in regular waves.

4. Damping Elements Considered for the Present Study

The review of literature indicates that the appendages in the form of circular disks seemed to be widely used in the past which has effective means of limiting the heave motion. Hence the present study deals with addition of heave plates in the form of circular disk to the Spar hull in two different configurations like, Spar with single heave plate at keel and Spar with double heave plate at certain spacing. In case of Spar with single heave plate, the diameter of the heave plate is varied in each case and their influence on hydrodynamic responses is investigated. In case of Spar with double heave plate, there are two heave plates with fixed disk diameter ratio (D_d/D_s) of 1.3 (Sudhakar and Nallayarasu (2011)) and the spacing between heave plates is varied. The details of heave plates with different disk diameter ratio and relative spacing are shown in Table 1. The Spar models with different heave plate configurations are shown in Fig. 2.

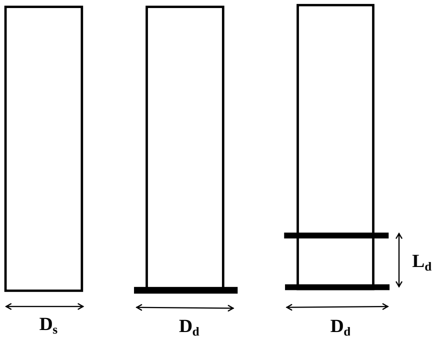


Fig. 2. Spar models with single and double heave plate configuration

Table 1. Geometric Parameters of Spar Models

Heave plate configuration	Geometric parameters	Heave plate diameter ratio					
		1.00	1.10	1.20	1.30	1.40	1.50
Spar	Spar diameter (cm)	25					
	Total draft (cm)	110					
Spar with single heave plate	Heave plate thickness (cm)	No Disk	0.5	0.5	0.5	0.5	0.5
	Heave plate diameter (cm)	No Disk	27.5	30	32.5	35	37.5
Spar with double heave plate	Heave plate thickness (cm)	------	0.5	0.5	0.5	0.5	0.5
	Disk diameter ratio (D_d/D_s)	1.30	1.30	1.30	1.30	1.30	1.30
	Heave plate diameter (cm)	32.5	32.5	32.5	32.5	32.5	32.5
	Relative Spacing (L_d/D_d)	------	0.1	0.2	0.3	0.4	0.5
	Relative Spacing (cm)	------	3.25	6.5	9.75	13.00	16.25

5. Experimental Investigation

The experimental studies were carried out in two phases as described below: (a) The first set of experiments were conducted to investigate the influence of diameter of the heave plate, and wave steepness, pretension in the mooring line on hydrodynamic responses (heave, surge and pitch) in regular waves. (b) The second set of experiments were carried out to understand the influence of relative spacing between the heave plates on hydrodynamic responses of the Spar attached with heave plate of disk diameter ratio 1.3 in regular waves.

5.1 Model Details

The Spar models were designed for a water depth of approximately 250 m with a payload of 10000 tonnes and fabricated in 1:100 scale using acrylic material. Froude scaling was adopted to arrive the model dimensions. The principal parts of the classic Spar model are vertical hollow cylinder, a deck plate at the top and a detachable heave plate at the bottom. The concentric acrylic cylinder of outer diameter 25 cm, an inner diameter 24 cm and of height 125 cm with closed bottom and top ends formed the main part. A steel deck plate of 35 cm x 35 cm x 1 cm was used as the deck plate to attain the topside weight. The details of prototype and scale model of classic Spar including dimension, payload and its hydrostatic properties are summarized in Table 2. In case of Spar with double heave plate, in addition to the bottom heave plate, another heave plate is also attached to the Spar at a relative spacing (L_d/D_d) varies from 0.1 to 0.5.

Table 2: Details of prototype and scale model

Description	Prototype	Scale model (1:100)
Water depth	245 m	2.45 m
Material	Steel	Acrylic
Unit weight	78.5 kN/m^3	12 kN/m^3
Deck size	35x35x1 m	0.35x0.35x0.01 m
Topside weight	98100 kN	98.1N
Draft	110 m	1.1 m
Free board	15 m	0.15 m
Diameter	25 m	0.25 m
Self weight	71613 kN	71.62 N
Weight due to ballast	357055 kN	357.1 N
Buoyancy force (B)	542944 kN	543 N
Vertical center of gravity from keel (VCG)	60.01 m	0.60 m
Vertical center of buoyancy from keel (VCB)	55 m	0.55 m
Metacentric height (GM)	5.38 m	0.0535 m
Wall thickness	95 mm	5 mm
Ratio of pretension to buoyancy force (T_N/B)	-	2.98% & 1.63%
Heave natural period	22 sec	2.24 sec
Pitch natural period	42 sec	4.2 sec

Table 3: Measured natural period and damping ratio of various configurations

Heave plate configuration	Parameters	Heave plate diameter ratio					
		1.00	1.10	1.20	1.30	1.40	1.50
Spar and Spar with single heave plate	Heave natural period $T_{N,3}$ (sec)	2.24	2.28	2.34	2.39	2.43	2.49
	Heave damping ratio ξ_3 (%)	4.3	5.6	6.4	7.0	7.7	8.3
Spar with double heave plate	Disk diameter ratio (D_d/D_s)	1.30	1.30	1.30	1.30	1.30	1.30
	Relative Spacing(L_d/D_d)	-----	0.1	0.2	0.3	0.4	0.5
	Heave natural period $T_{N,3}$ (sec)	-----	2.396	2.41	2.415	2.416	2.420
	Heave damping ratio ξ_3 (%)	-----	7.96	8.47	9.36	10.13	10.47

5.2 Instrumentation

The wave surface elevation was measured using resistance type wave probes. The measurement of surge, heave and pitch accelerations was carried out using inductive type accelerometers mounted at the deck of Spar model as shown in Fig. 3(b). Four single component ring-type load cells with a maximum capacity of 25 N were used to measure the mooring line tension. Foil type strain gauges of 5 mm long were used in conjunction with a Wheatstone full bridge configuration. The strain gauges were protected by epoxy coating to protect it from moisture.

5.3 Test Facility

The experimental investigations were carried out in 90 m long, 4 m wide and 3 m deep wave flume in the Department of Ocean Engineering, Indian Institute of Technology Madras, India. The wave flume is equipped with a dual hinged flap type wave maker which is controlled by hydraulic system. The wave maker is capable of generating regular waves of different wave heights and frequencies, as well as random waves of predefined spectral characteristics. The other end of the flume is provided with rubble mound artificial beach with an average slope of 1:6 to absorb the incident waves. The size of the flume is sufficient to simulate intermediate and deep water conditions (d/L = 0.208-1.57) in the model test. Also the size of the model (diameter = 0.25m) to size of the flume (width = 4m) is less than 10%, the side wall effects are also negligible. A photographic view of the 4m wave flume is shown in Fig. 3(a). The elevation and plan views of the 4m wave flume along with the location of the Spar model with single heave plate and wave gauge for the response measurement studies is incorporated in Fig. 4.

(a) (b)

Fig. 3. Wave flume facility and scale model of Spar with instrumentation (a) Test facility (b) Scale model of Spar

Table 4. Measured hydrodynamic response of the system in regular waves

Mooring Configuration	Heave plate configuration	Disk Diameter Ratio (D_d/D_s)	Relative Spacing (L_d/D_d)	Maximum RAO Surge (cm/cm)	Peak RAO Heave (cm/cm)	Peak RAO Pitch (deg/cm)
Taut 45˚	Spar	1.0	-----	1.74	2.18	0.132
	Spar with single heave plate(at keel)	1.1	-----	1.68	2.14	0.127
		1.2	-----	1.67	1.92	0.123
		1.3	-----	1.55	1.82	0.115
		1.4	-----	1.45	1.70	0.108
		1.5	-----	1.40	1.66	0.104
Slack	Spar	1.0	-----	2.10	4.45	0.880
	Spar with single heave plate(at keel)	1.1	-----	2.04	3.56	0.841
		1.2	-----	1.85	3.18	0.756
		1.3	-----	1.69	2.98	0.643
		1.4	-----	1.62	2.88	0.600
		1.5	-----	1.60	2.82	0.580
Slack	Spar with double heave plate	1.3	0.1	1.56	2.92	0.619
		1.3	0.2	1.41	2.70	0.580
		1.3	0.3	1.28	2.60	0.523
		1.3	0.4	1.22	2.28	0.484
		1.3	0.5	1.20	2.20	0.460

5.4 Experimental Setup

The scale models were positioned at a distance of 25 m from the wave maker as shown in Fig. 3(b). The model was moored with four mooring lines of strand type twisted steel wire rope of 3mm diameter. One end of each mooring line was connected to the fairleader points (mid distance between center of gravity and center of buoyancy) on the Spar model and the other end to a rigid concrete block. Regular wave tests were conducted with both taut and slack mooring in all the models. The mooring line has a base angle of 45˚ to the flume bed in case of taut mooring. The mooring lines were applied with pretension force of 2.98% and 1.63% of the buoyancy force, with the constant payload at two pretension levels in case of taut mooring. The adjustment mechanism provided at the upper end of the steel wire rope permitted increase in pretension thereby permitting a corresponding draft change in the Sparhull. The measured responses and mooring line forces were recorded with a help of a data acquisition system. The sampling rate of data acquisition was set to 25Hz in regular wave test.

5.5 Heave Oscillation Tests

Heave oscillation tests were carried out in still water for three different configurations such as Spar, Spar with heave plate at keel and Spar with double heave plate. The model was given an initial displacement and the subsequent motions were recorded. The measured time history of the Spar alone and Spar with heave plate at the keel ($D_d/D_s = 1.5$) in heave mode is shown in Fig. 5. The time series from heave oscillation tests were used for estimating the damping ratio and the natural period of each configuration. The damping ratio was estimated from the logarithmic decrement method of successive cycles. The test results are summarized in Table3.

5.6 Regular Wave Tests

A series of regular wave tests were carried out for all the models over a range of wave periods from 1.0 to 2.8 sec at an interval of 0.1 sec for wave heights of 3 cm and 5 cm. The measured time histories of heave and surge acceleration of the Spar model are shown in Fig. 6. The measured hydrodynamic responses and mooring line tension in regular waves are presented as transfer function. The amplitude of the response is normalized with the amplitude of incoming wave as a function of the wave period and is represented as the response amplitude operator (RAO).

Surge RAO = Surge amplitude/wave amplitude

Heave RAO = Heave amplitude/wave amplitude

Pitch RAO = Pitch amplitude/wave amplitude

Mooring tension RAO = Mooring tension amplitude/wave amplitude

The measured peak and maximum RAOs of the system in the tested range are given in Table 4.

6. Numerical Investigation

The numerical simulation of the model Spar and Spar with single and double heave plates have been carried out using ANSYS AQWA. It is a diffraction radiation program based on linear potential theory. It works on the principle of panel methods.

6.1 Wave Parameters

The numerical simulation was carried out for the wave periods ranging from 1.0 to 3.0 sec which corresponds to a wave length of 1.56 m to 14.04 m in a water depth of 2.45 m. Based on parameters such as wave length (L), water depth (d), wave height (H) and the characteristics body dimension along the horizontal plane (Diameter, D), the non dimensional ratios can be formed such as Steepness parameter (H/L), depth parameter (d/L) and scattering or diffraction parameter (D/L) can be formed and the details are summarized in Table 5.

6.2 Computational Methodology

Numerical simulation of hydrodynamic response of Spar with and without rigid heave plates (both single and double heave plate) has been carried out in time domain using hydrodynamic software package ANSYS AQWA. The simulated 3D surface is shown in Fig. 7. A convergence study was carried out to examine the effect of size of the elements for the structure and finally the hydrodynamic analysis was performed with the chosen element size of 2 cm in the model configurations. Several other inputs such as mass of the structure, radius of gyration/moment of inertia etc. are provided to the program externally.

Table 5. Range of dimensionless parameters

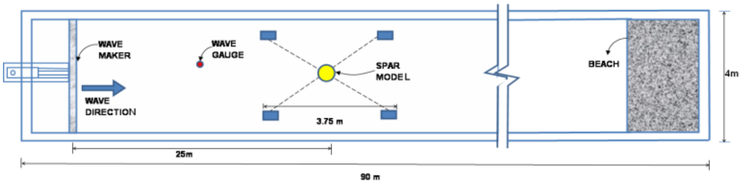
Description	**Parameters**	**Range**
Spar and Spar with heave plate	Wave steepness parameter (H/L)	0.0036-0.032
	Diffraction parameter(D/L)	0.018-0.16
	Depth parameter (d/L)	0.17-1.57

Table 6. External input parameters for Spar in numerical simulation

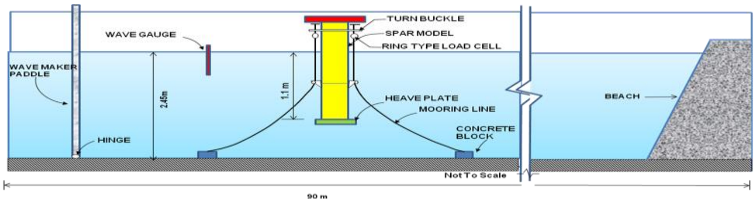
Parameters	**Numerical input values**
Center of gravity	$C_{xx} = 0$ $C_{yy} = 0$ $C_{zz} = -59.75$ cm
Radius of gyration	$R_{xx} = 78.68$ cm $R_{yy} = 78.68$ cm $R_{zz} = 10.14$ cm

Table 7. External damping (%) for Spar alone and Spar with single and double heave plate

Heave plate configuration	**Disk Diameter ratio (D_d/D_s)**	**Relative Spacing (L_d/D_d)**	**Total Damping Experiment (%)**	**Simulated radiation damping (%)**	**External Damping input to Numerical simulation (%)**
Spar with single heave plate	1.0	-----	4.30	0.096	4.204
	1.3	-----	7.00	0.112	6.888
Spar with double heave plate	1.5	-----	8.30	0.115	8.185
	1.3	0.1	7.96	0.124	7.846
	1.3	0.3	9.36	0.125	9.235
	1.3	0.5	10.47	0.126	10.344



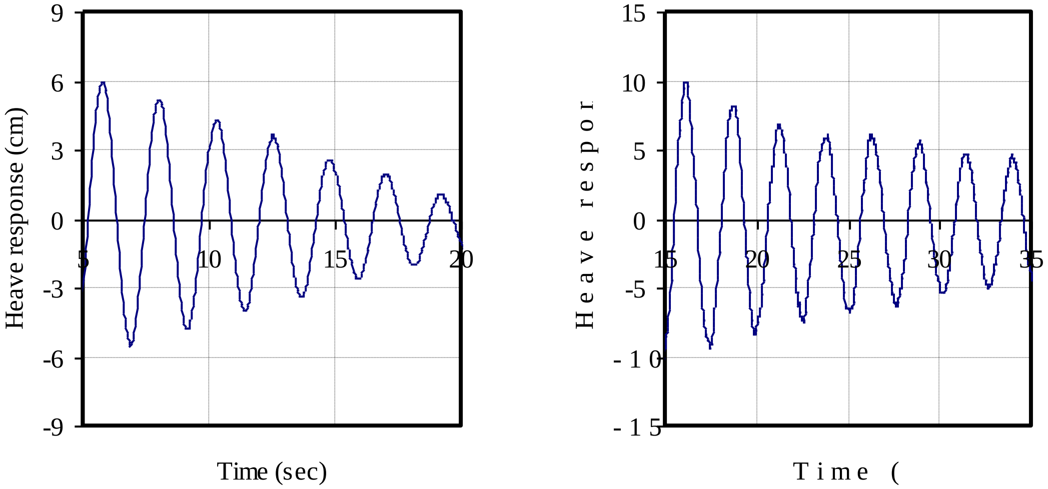
(a) Plan



(b) Elevation

Fig. 4. Experimental setup of Spar with single heave plate in wave flume (N.T.S.)

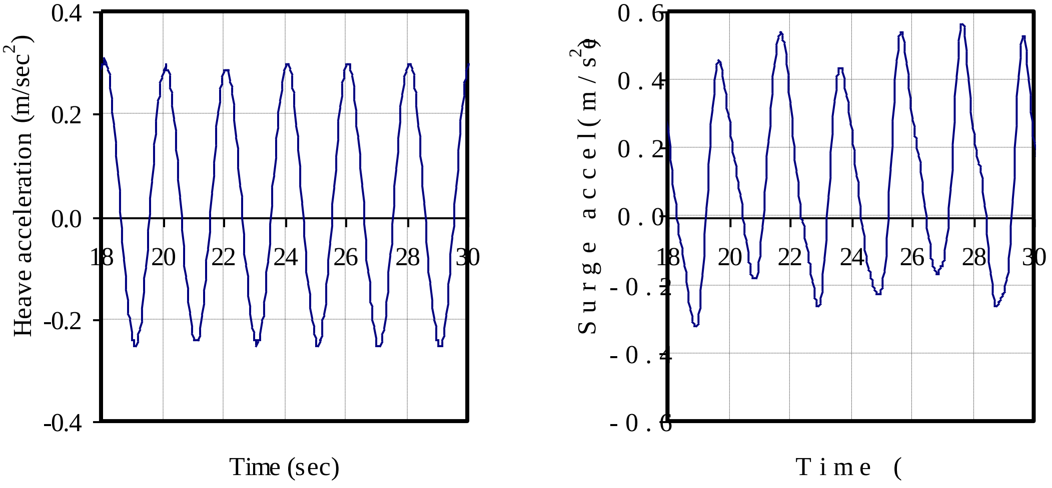
The inputs used for numerical simulation of hydrodynamic response of the Classic Spar are presented in Table 6. The software considers only radiation damping and the effect of viscous damping are not automatically generated. In order to include the viscous damping, external damping is input into the numerical analysis in heave and pitch mode. This is taken as the difference between the results obtained from free decay tests and the radiation damping obtained from the numerical analysis. The typical external damping inputs applied in heave mode in case of Spar with single and double heave plate at heave resonant condition are presented in Table 7. The mooring line attached to the system is modeled as a linear elastic weightless spring, with constant line stiffness. The properties of the mooring lines are specified in the input file as their outstretched lengths, end nodes on respective bodies and their load/extension characteristics.



(a) D_d/D_s= 1.0

(b) D_d/D_s = 1.5

Fig. 5. Measured heave decay records of (a) Spar (b) Spar with heave plate at the keel



(a) Heave acceleration

(b) Surge acceleration

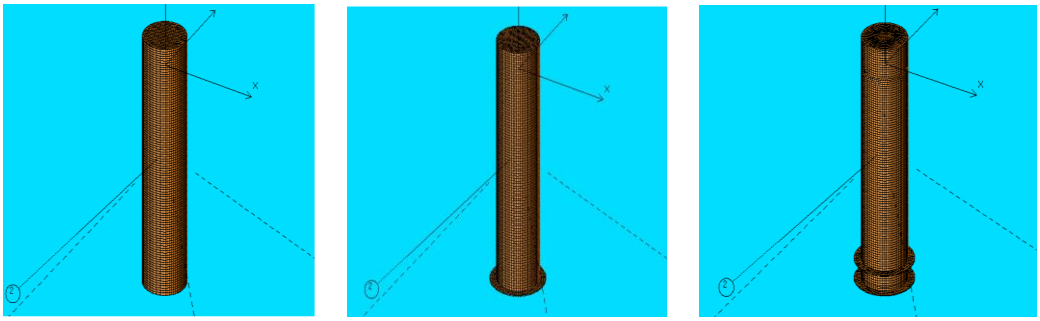
Fig. 6. Measured time history of Spar in regular waves

7. Results and Discussion

The experiments were carried out using scale model of Spar, Spar with single and double heave plates. The numerical simulations have been carried out using ANSYS AQWA. The simulated hydrodynamic responses were compared with measured hydrodynamic responses and presented.

7.1 Comparison of experimental and simulated results

The measured and simulated results of the RAOs (heave, surge and pitch) of the Spar alone, Spar with single and double heave plates for slack mooring system are shown in Figs. 8 to 13. It is observed that, the measured heave responses were found to be in good agreement with that obtained from numerical simulation (Fig. 8 (a)). The maximum difference in peak heave response is less than 9%. The difference could be attributed to the fact that the viscous damping is modeled with linear frequency independent term in the numerical simulation. However, viscous drag effects dominate the damping and consequently the damping has non linear relation with hydrodynamic responses. The surge RAO obtained from experimental investigation is about the top of the Spar. It is shifted to the center of gravity (VCG) of the system since the responses were obtained in the centre of gravity incase of numerical simulation. Comparison also indicates that the measured surge response (Fig. 10(a)) matches reasonably well with the simulated results at lower wave period. However, the average difference between the experimental and results obtained from numerical simulation is 18% in higher wave periods. The comparison of pitch RAO (Fig. 12(a)) indicates that the experimental results are marginally higher for larger wave periods, including the peak value. The maximum difference in peak responses is found to be 10%. Similar trends are also observed for the Spar with single heave plate with disk diameter ratios (D_d/D_s=1.3 & 1.5), as shown in Figs. 8, 10 & 12 for heave, surge and pitch respectively. The maximum difference in peak heave response is found to be 7% and 11% respectively. The average difference in maximum surge response in higher wave periods is observed to 12% & 8% respectively. The maximum difference in peak pitch response is found to be 14% and 12% respectively. The measured pitch, surge and heave RAO compare reasonably well with that of the numerically simulated results in case of Spar with double heave plate (Figs. 9(b), 11(b) & 13(b)) at relative spacing (L_d/D_d) equal to 0.3. The maximum difference is observed to be 14%, 16% and 10% for the pitch, surge and heave respectively. Similar trend is observed in other relative spacing such as 0.1 and 0.5.



(a) D_d/D_s=1.0 (b) D_d/D_s= 1.3 (c) L_d/D_d= 0.3

Fig. 7. Numerical models (a) Spar (b) Spar with single heave plate (c) Spar with double heave plate

7.2 Motion Response of Spar and Spar with Single Heave Plate

The motion response characteristics of Spar and Spar with single heave plate are presented in the form of RAO as a function of wave period. The influence of disk diameter ratio on heave added mass, viscous damping and hydrodynamic responses of Spar and Spar with single heave plate is discussed. The effect of varying wave steepness, pretension in the mooring line and type of mooring on hydrodynamic responses has been carried out as the parametric study.

7.2.1 Effect of disk diameter ratio on heave added mass

The variation of heave added mass with wave period obtained from the numerical simulation for the Spar alone and Spar with single heave plate having different disk diameter ratio is presented in Fig. 14(a). It is observed that the variation of heave added mass is constant across the wave period. This may be attributed to the fact that the heave added mass effect is felt near the keel of the Spar, which is much far from the wave surface. Hence it is least affected by the wave periods. It is also observed that the heave added mass increases with increase in disk diameter ratio for all the wave periods. The simulated peak heave added mass with disk diameter ratio is also shown in Fig. 14(b). It is observed that, the increase in peak heave added mass is steep beyond the disk diameter ratio of 1.2. As the disk diameter ratio (D_d/D_s) increases from 1 to 1.2 the heave added mass increases by 50%; when D_d/D_s was increased to 1.5, the induced added mass shoots up by 200%. Hence the heave added mass increases four-fold when the diameter ratio increases from 1.2 to 1.5.

7.2.2 Effect of Disk Diameter Ratio on Viscous Damping

The variation of heave damping ratio for Spar with different disk diameter ratio is presented in Fig. 14(c). The heave damping ratio of Spar increases from 4.3% to 6.4% on the addition of heave plate of disk diameter ratio of 1.2. By employing larger heave plate of disk diameter ratio of 1.5, the heave damping ratio further increases to 8.3%. Hence the percentage increase is 49% and 93% respectively when with classic Spar. The addition of heave plate enhances the vortex shedding process and hence the viscous damping. For a heave plate with smaller diameter, the vortices formed will be suppressed by the cylinder walls, resulting in lesser increase in damping. On the other hand, vortices at larger size heave plate are more rounded and appear to move around without the cylinder’s hindrance. Due to the formation of strong vortex shedding process, the percentage increase in damping ratio is high in case of Spar with larger heave plate.

7.2.3 Effect of Geometry on Motion Response

The variation of heave, surge and pitch RAO measured from the model tests for the Spar and Spar with heave plate as a function of wave period is shown in Fig. 15. The heave RAO increases with increase in wave period up to heave natural period, after which it starts decreasing with increase in wave period. The trend is similar for all the configurations except that of the peak values of RAO which occur at different wave periods. The shift in peak could be attributed to the increase in heave added mass on the addition of single heave plate. The peak heave RAO of the Spar reduces from 4.45 cm/cm to 2.98 cm/cm (Fig. 15(a)) on the addition of single heave plate of disk diameter ratio 1.3. The peak heave RAO is further reduced from 2.98 cm/cm to 2.82 cm/cm as the disk diameter ratio (D_d/D_s) increases from 1.0 to 1.5. Hence the decrease in peak heave response is as much as 37% for the increase of rigid plate size by 50%.The reduction in peak heave responses is partially due to increase in viscous damping, but also to the fact that the increase in heave added mass leading to increase in heave natural period resulting reduced heave motion.

The maximum surge RAO of the Spar reduces (Fig. 15(b)) from 2.1 cm/cm to 1.69 cm/cm on the addition of single heave plate of disk diameter ratio 1.3. Hence, the reduction in surge response is about 19.5% for the increase of plate size by 30%.The maximum surge RAO further reduces from 1.69 cm/cm to 1.6cm/cm as disk diameter ratio (D_d/D_s) increases from 1.0 to 1.5. Hence, the decrease in maximum surge RAO is about 24% for the increase of plate size by 50%.

The measured results show that the pitch RAO (Fig. 15(c)) increases with increase in wave period to a peak value of 0.88 deg/cm for Spar alone and a peak value of 0.58 deg/cm incase of Spar with single heave plate(D_d/D_s=1.5). Hence, the reduction in pitch RAO is about 33% for the increase of plate size by 50%. This reduction in pitch response may be attributed to the increase in pitch added mass due to the heave plate as well as the increased pitch damping due to larger plate size.

7.2.4 Influence of Disk Diameter Ratio on Motion Response

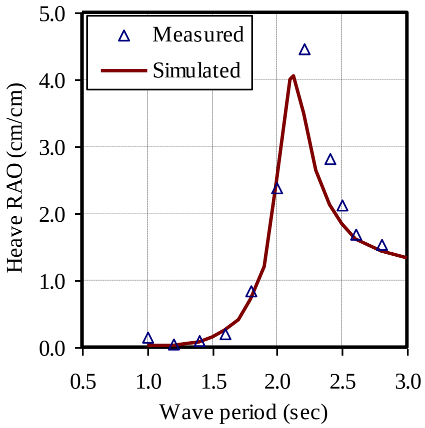
The variation of peak heave and pitch RAO and maximum surge RAO with the disk diameter ratio (D_d/D_s) in case of Spar with single heave plate is shown Fig. 16. The peak heave RAO shows a decreasing trend with increase in disk diameter ratio. Similar trend in reduction of maximum surge RAO and peak pitch RAO is observed. However, the decrease in surge and heave RAO is very small for disk diameter ratio greater than 1.3. This indicates that any further increase in diameter of the heave plate, the reduction in responses such as heave, surge and pitch will be minimum. Hence the optimum heave plate size shall be restricted to 20% to 30% larger than the diameter of the Spar to achieve the optimum response.

7.2.5 Influence of Wave Steepness on Motion Response

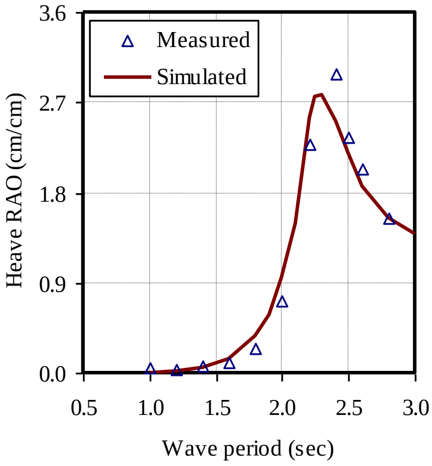
The measured heave and surge RAO for two wave steepness values of 0.011 & 0.018 are shown in Fig. 17(a) & (b) respectively. The peak heave RAO for wave steepness of 0.01 and 0.018 are 2.42 cm/cm and 2.18 cm/cm respectively. The trend of the RAO indicates that the heave RAO decreases with increase in wave steepness. Hence the reduction of peak heave RAO is about 10%. This reduction in heave response is due to increased damping with the increase in wave steepness. It is also observed that the surge RAO increases marginally with a maximum increase of 5% as the wave steepness increases.

7.2.6 Influence of Pretension in the Mooring Line on Heave Response

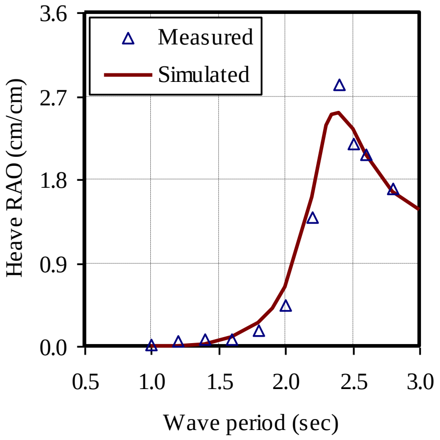
The measured heave RAO for mooring pretension ratio T_N/B (where T_N = total tension in the mooring line and B is the buoyancy force) of 1.63% & 2.98% are presented in Fig. 17(c). The peak heave RAO of the Spar for the specified two pretension levels in the mooring lines at 2.2 sec is 2.18 cm/cm and 2.45 cm/cm respectively. The reduction in peak RAO is about 10% for the increase of pretension ratio from 1.63% to 2.98%. At lower wave periods (1.0 to 2.0sec), the reduction in heave response is marginal. i.e., the reduction is less than 5%. Hence it can be concluded that the effect of pretension on the heave response is very limited. Further it shall be noted that the reduction in heave RAO by means of increasing pretension will be at the cost of reduction in pay load, if the draft has to be maintained. Hence selection of pretension should be carefully considered together with the required payload.



(a) $D_d/D_s = 1.0$

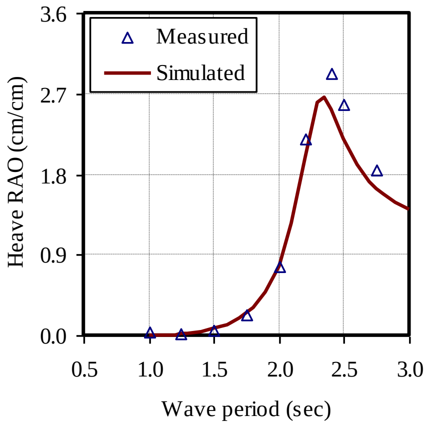


(b) $D_d/D_s = 1.3$

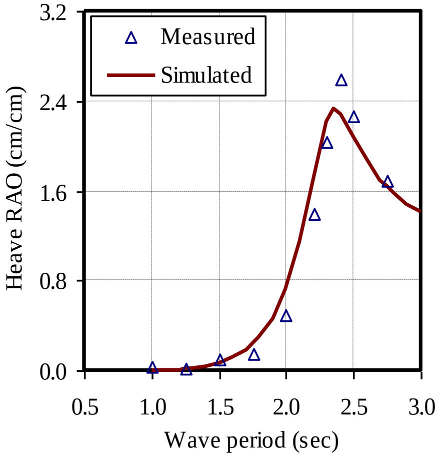


(c) $D_d/D_s = 1.5$

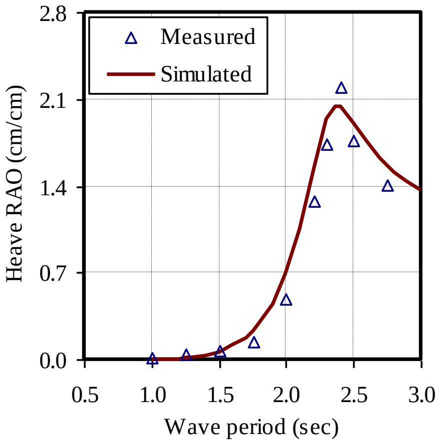
Fig. 8. Comparison of measured and simulated heave response for Spar and Spar with single heave plate



(a) $L_d/D_d = 0.1$

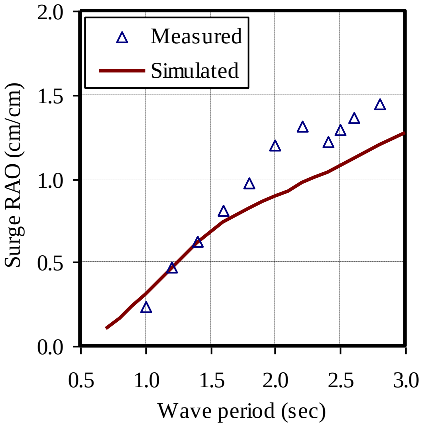


(b) $L_d/D_d = 0.3$

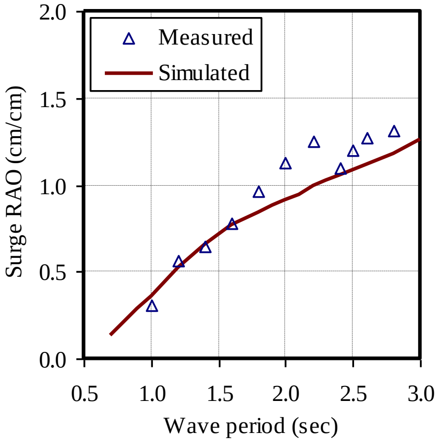


(c) $L_d/D_d = 0.5$

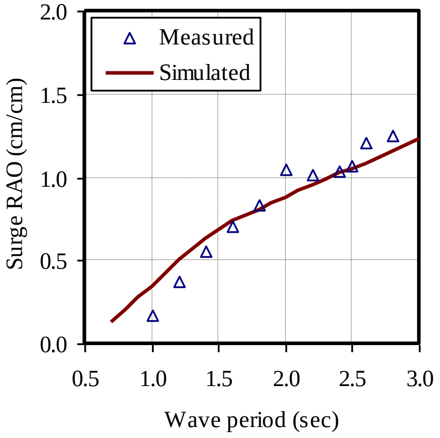
Fig. 9. Comparison of measure and simulated heave response for Spar with double heave plate



(a) D_d/D_s=1.0

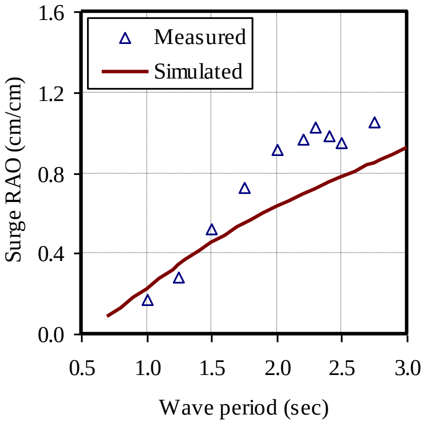


(b) D_d/D_s = 1.3

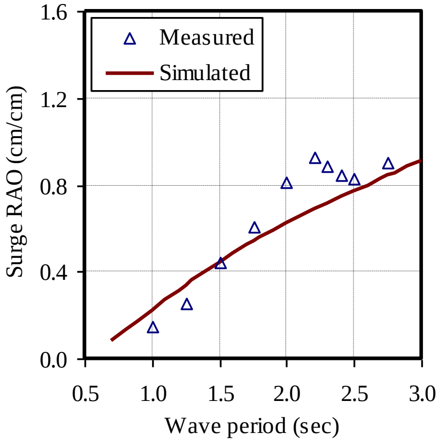


(c) D_d/D_s = 1.5

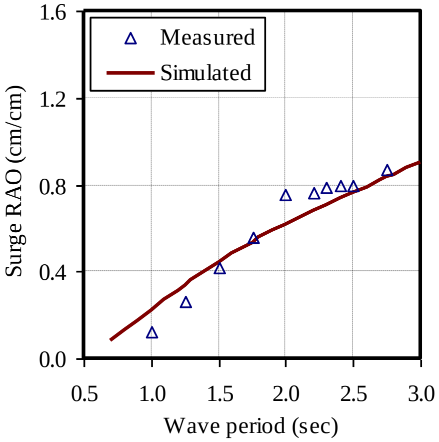
Fig. 10. Comparison of measured and simulated surge response for Spar and Spar with single heave plate



(a) L_d/D_d = 0.1

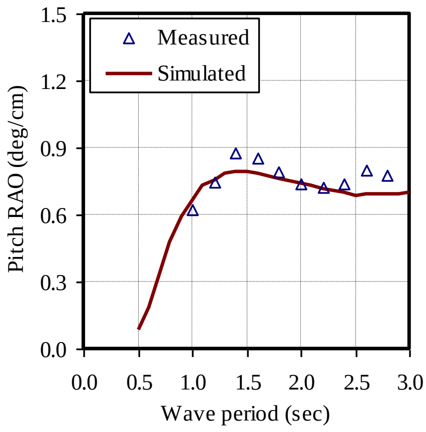


(b) L_d/D_d = 0.3

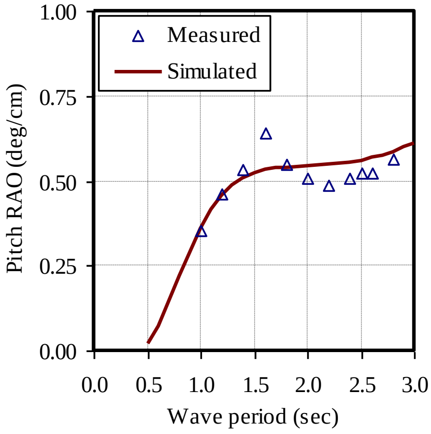


(c) L_d/D_d = 0.5

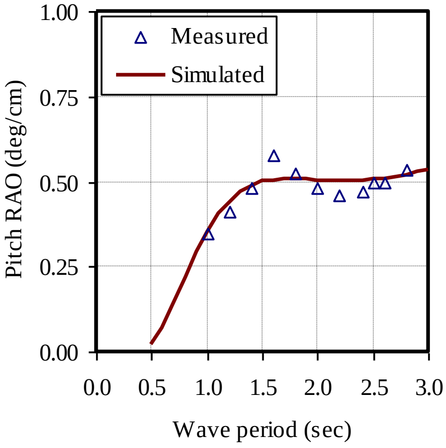
Fig. 11. Comparison of measure and simulated surge response for Spar with double heave plate



(a) $D_d/D_s = 1.0$

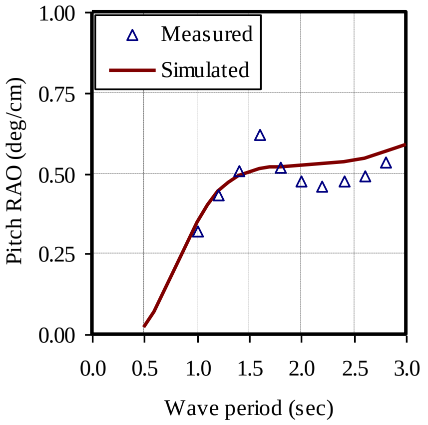


(b) $D_d/D_s = 1.3$

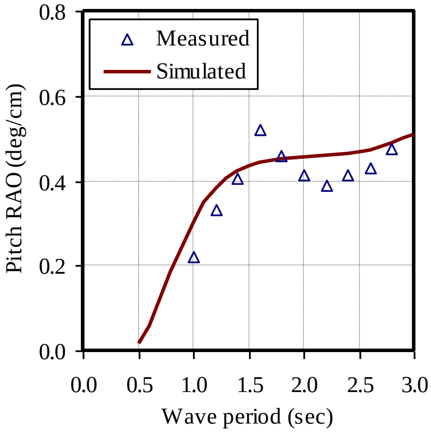


(c) $D_d/D_s = 1.5$

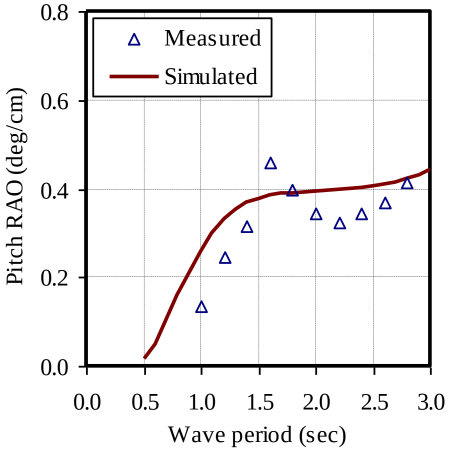
Fig. 12. Comparison of measured and simulated pitch response for Spar and Spar with single heave plate



(a) $L_d/D_d = 0.1$

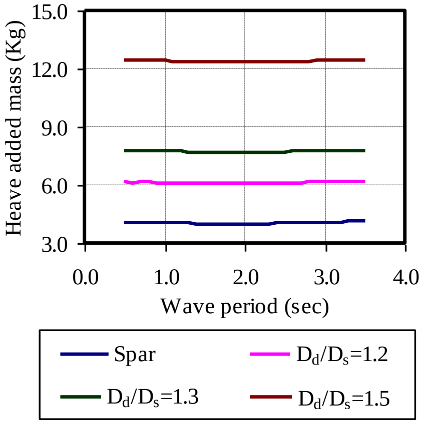


(b) $L_d/D_d = 0.3$

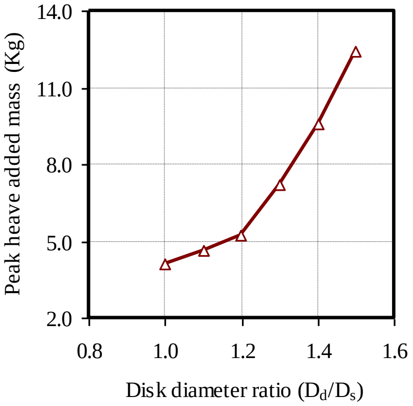


(c) $L_d/D_d = 0.5$

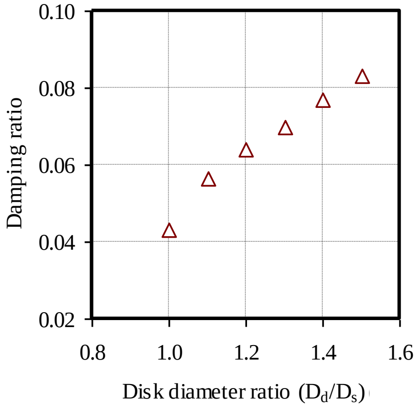
Fig. 13. Comparison of measure and simulated pitch response for Spar with double heave plate



(a) Heave added mass

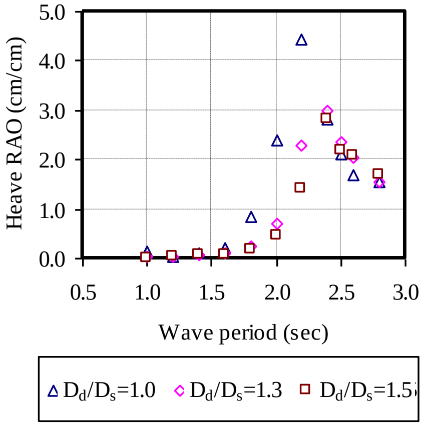


(b) Peak heave added mass

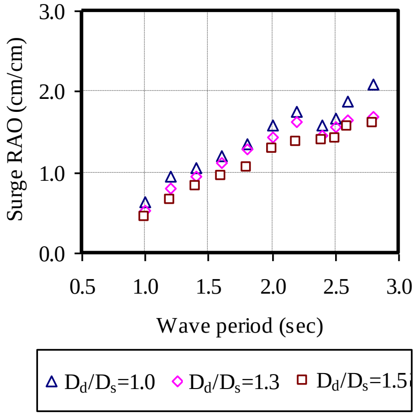


(c) Heave damping ratio

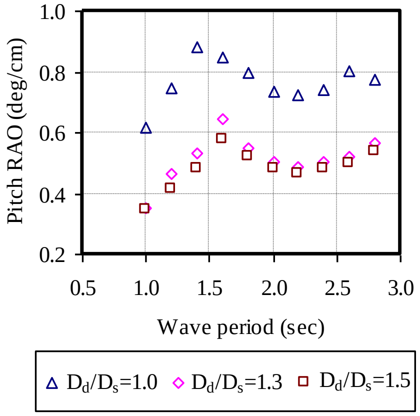
Fig. 14. (a)Variation of heave added mass with wave period (b) peak heave added mass as a function of disk diameter ratio(c) heave damping ratio as a function of disk diameter ratio



(a) Heave

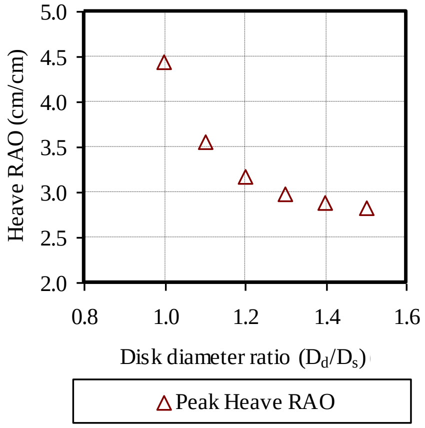


(b) Surge

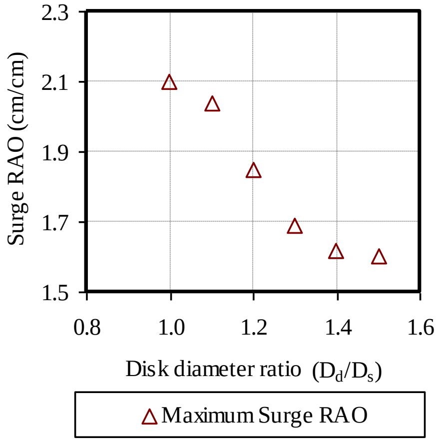


(c) Pitch

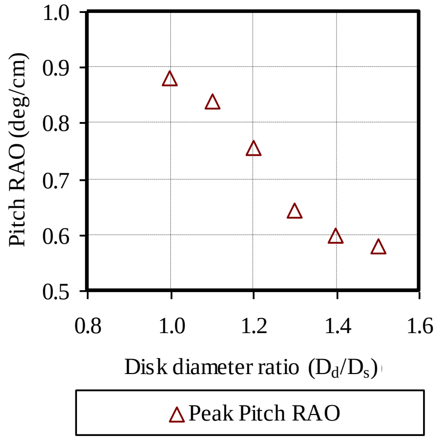
Fig. 15. Variation of heave, surge and pitch response with wave period for Spar and Spar with single heave plate.



(a) Heave

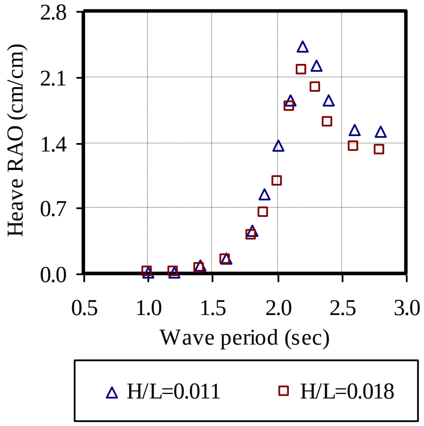


(b) Surge

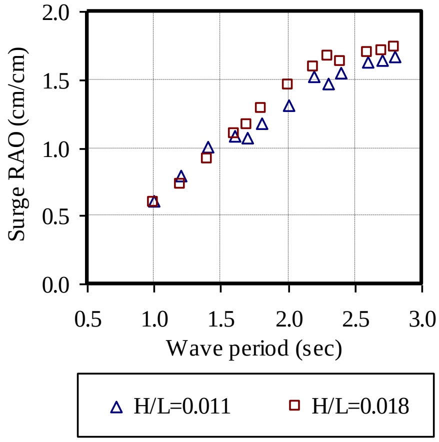


(c) Pitch

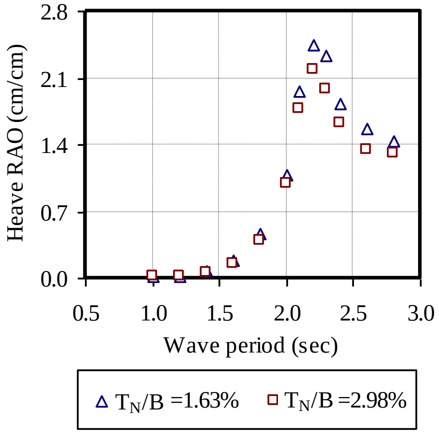
Fig. 16. Variation of peak heave, pitch responses and Maximum surge response as a function of disk diameter ratio



(a) Heave

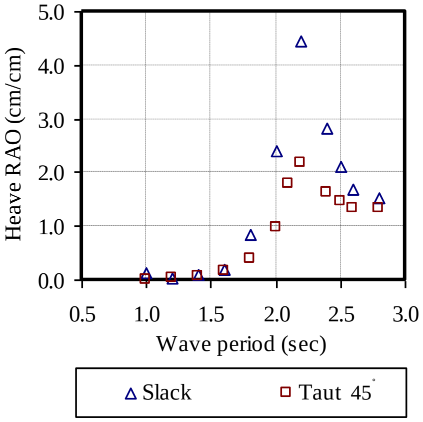


(b) Surge

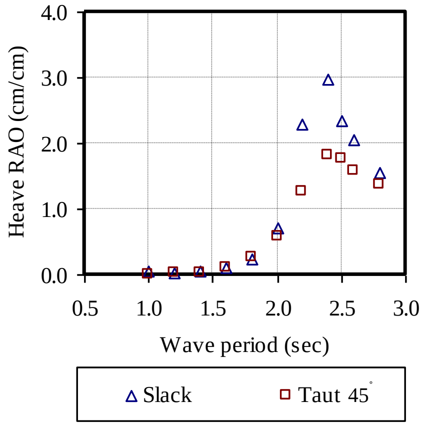


(c) Heave

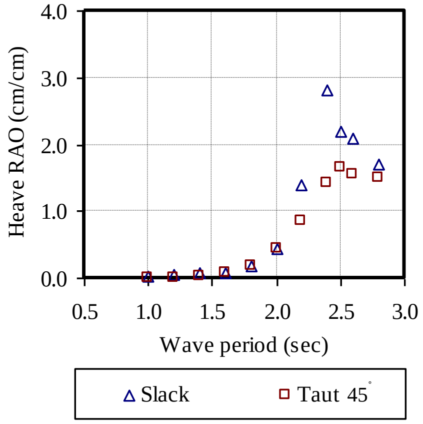
Fig. 17. Influence of wave steepness on (a) heave response (b) surge response (c) Influence of pretension(T_N) on heave response



(a) $D_d/D_s = 1.0$

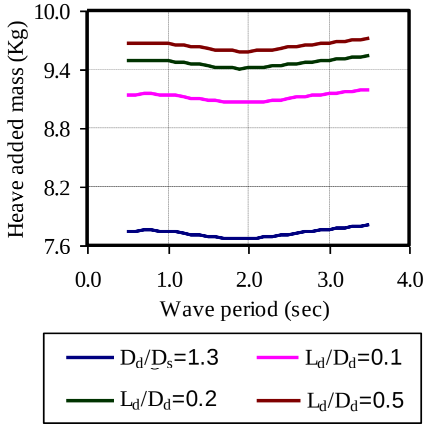


(b) $D_d/D_s = 1.3$

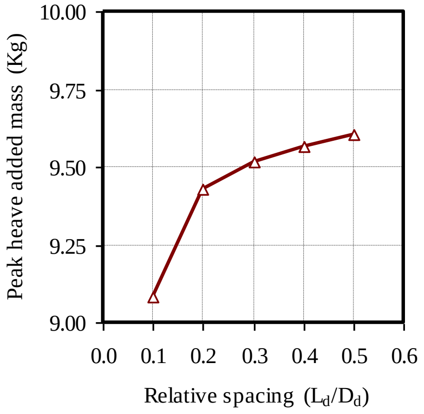


(c) $D_d/D_s = 1.5$

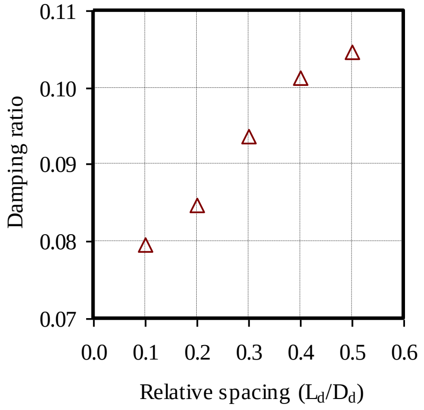
Fig. 18. Influence of mooring type on heave response for Spar and Spar with single heave plate



(a) Heave added mass

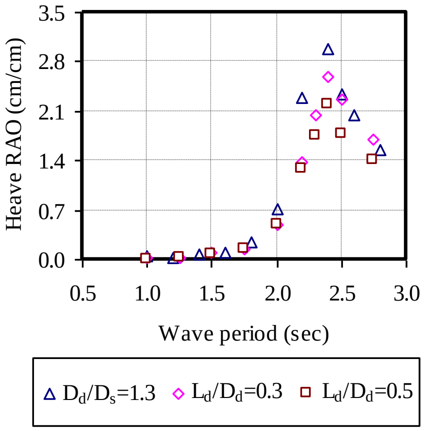


(b) Peak heave added mass

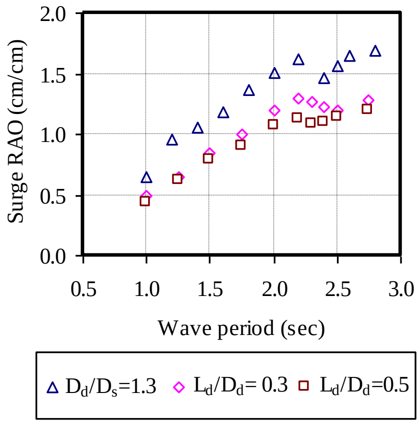


(c) Heave damping ratio

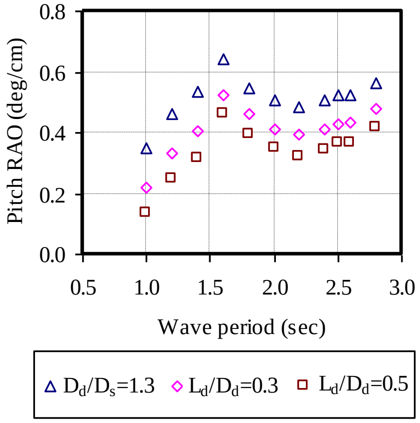
Fig. 19. (a) Variation of heave added mass with wave period (b) peak heave added mass as a function of relative spacing (c) heave damping ratio as a function of relative spacing



(a) Heave

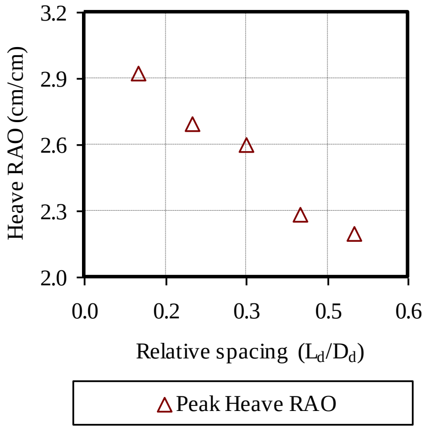


(b)Surge

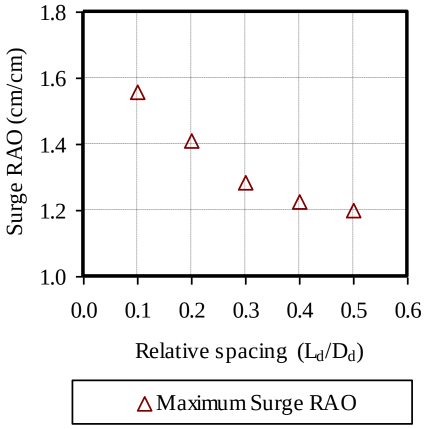


(c) Pitch

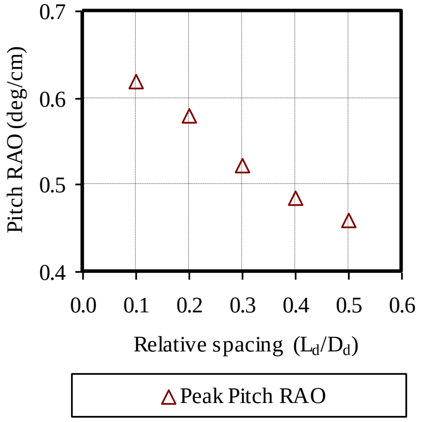
Fig. 20. Variation of heave, surge and pitch response with wave period for Spar with single and double heave plate



(a) Heave

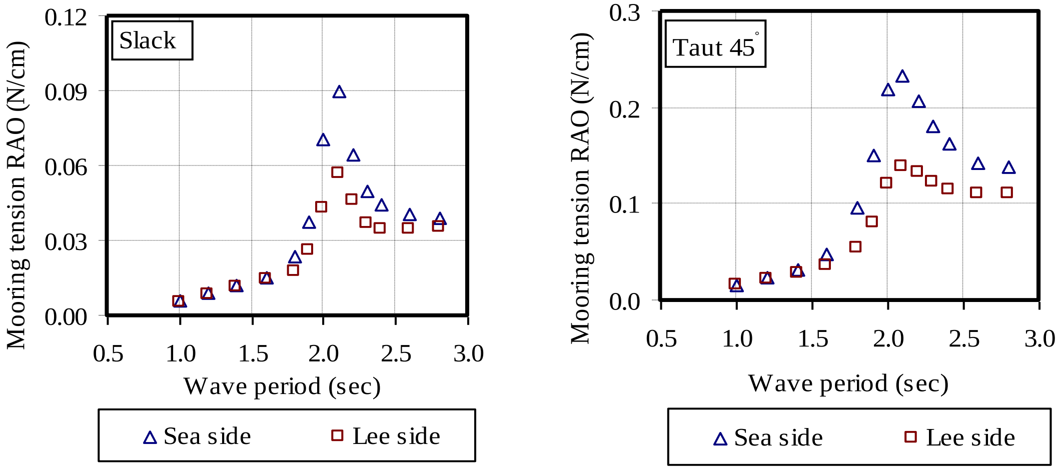


(b) Surge



(c) Pitch

Fig. 21. Variation of peak heave, pitch response and maximum surge response as a function of relative spacing



(a) (b)

Fig. 22. Mooring tension responses of Spar (a) Slack mooring (b) taut 45° mooring

7.2.7 Influence of Type of Mooring on Heave Response

The measured RAOs of the Spar alone and the Spar with single heave plate of different disk diameter ratio with slack and taut 45° mooring are shown in Fig. 18. It is observed that the peak heave RAO of the Spar gets reduced by about 51% for taut 45° mooring when compared to slack mooring in regular waves. The reduction in heave response is marginal at lower wave periods. Similar trend is followed in other heave plate configurations. There is a reduction in peak heave response of the Spar with heave plate of disk diameter ratio of 1.3 and 1.5 by 39% and 41% respectively.

7.3 Motion Response of Spar With Double Heave Plate

The motion response characteristics of Spar with double heave plate are obtained experimentally and the results are presented in the form of RAO as a function of wave period. The influence of relative spacing on heave added mass, viscous damping and hydrodynamic responses are discussed.

7.3.1 Effect of Relative Spacing on Heave Added Mass

The variation of heave added mass with wave period obtained from the numerical simulation is presented in Fig. 19(a). It is clearly indicated that, the variation of heave added mass with wave period is constant. As the relative spacing (L_d/D_d) between the plates increases, the heave added mass also increases for all the wave periods. The simulated peak heave added mass expressed in terms of relative spacing is also shown in Fig. 19(b). The peak heave added mass increases by 24.8% in case of Spar with double heave plate (L_d/D_d= 0.5) than the Spar with single heave plate. It is also found that the heave added mass vs. relative spacing curve become flatter beyond relative spacing of 0.3. i.e., the percentage increase in heave added mass is marginal beyond this limit. Hence it is concluded that, the heave added mass will become less dependent on the spacing between the plates beyond relative spacing of 0.3.

7.3.2 Effect of Relative Spacing on Viscous Damping

The variation of heave damping ratio in case of Spar with different heave plate configurations are presented in Fig. 19(c). The heave damping ratio of Spar with heave plate (D_d/D_s = 1.3), increases from

7% to 8.47% on the addition of another heave plate at relative spacing of 0.2. As the relative spacing increases from 0.2 to 0.5, the heave damping ratio is further increased to 10.47%. Hence the percentage increase is 21% and 50% respectively in comparison with Spar with single heave plate. As the spacing between the heave plates increases, the interaction of the vortices produced by the two plates will be less. So the net vortex shedding process will be more and hence the significant increase in percentage of damping is observed. But the increase in viscous damping is marginal, beyond the relative spacing of 0.4. Hence it is concluded that the viscous damping become independent on relative spacing beyond this limit.

7.3.3 Effect of Geometry on Motion Response

The variation heave, surge and pitch RAO measured from the model tests for the Spar with heave plate and Spar with double heave plate as a function of wave period is shown in Fig. 20. It is observed that, the peak heave RAO of the Spar with heave plate is reduced from 2.98 cm/cm to 2.2 cm/cm (Fig. 20(a)) on addition of double heave plate (L_d/D_d= 0.5), the reduction is nearly 26%. The reduction in peak heave responses is partially due to increase in viscous damping, and also due to the increase in heave added mass.

The maximum surge RAO of the Spar with single heave plate is reduced from 1.69 cm/cm to 1.2 cm/cm (Fig. 20(b)) on the addition of another heave plate at relative spacing of 0.5. Hence it is concluded that, the decrease in maximum surge RAO is about 30% for the increase of relative spacing by 0.5.

The peak pitch RAO of the Spar with single heave plate (D_d/D_s= 1.3) is further reduced from 0.643 deg/cm to 0.46 deg/cm (Fig. 20(c)) on the addition of another heave plate at relative spacing of 0.5. Hence the reduction in pitch response is about 27% for the increase of relative spacing by 0.5. This reduction in pitch response may be attributed to the increase in pitch added mass as well as the increase in pitch damping.

7.3.4 Effect of Relative Spacing on Motion Response

The variation of peak heave, surge and pitch RAO with the relative spacing of Spar with double heave plates is shown Fig. 21. The peak heave response reduces as the relative spacing increases. Similar trend in reduction of surge and pitch RAO is observed but the reduction is steep in the initial increase of relative spacing up to 0.4. i.e., the reduction in responses such as heave, surge and pitch will be minimum beyond this limit. Hence the optimum spacing between the heave plates shall be restricted to 30% to 40% larger than the diameter of the heave plate of disk diameter ratio 1.3 in order to achieve the optimum response.

7.4 Mooring Tension Response of Spar

The measured mooring tension RAOs for the seaside and leeside mooring lines of the Spar alone is shown in Fig. 22. It is to be noted that the mooring tension RAOs were averaged for sea side (two lines) and leeside (two lines). It is observed that, the peak mooring tension RAO for seaside mooring lines is higher by 37% and 41% for taut 45° and slack mooring respectively in comparison with the leeside mooring lines of the Spar. The seaside and leeside peak mooring tension RAO for taut 45° mooring cases increases by 160% and 142% respectively in comparison with slack mooring line for the Spar alone. This is due to the fact that the stiffness of the taut mooring lines is higher compared to slack mooring lines.

7.5 Effect of Disk Diameter Ratio on Mooring Tension Response

The measured average mooring tension RAOs for the sea side mooring lines of the Spar and Spar with heave plate of disk diameter ratio(D_d/D_s=1.5) are shown in Fig. 23. It is observed that, the peak mooring tension RAO of the Spar reduces by 17% and 30% for taut 45° and slack mooring respectively compared to the Spar with single heave plate. This may be attributed to the fact that the use of heave plates reduces the heave excitation force due to increase in heave added mass as discussed earlier.

8. Conclusion

An experimental study on hydrodynamic response of Spar with single and double heave plates was conducted on 1:100 scaled models in a laboratory wave flume. The influence of disk diameter ratio, relative spacing, pretension in the mooring line and wave steepness on the hydrodynamic responses has been studied. Numerical simulations were carried out using ANSYS AQWA and compared with measured hydrodynamic response. The following conclusions can be drawn from the present study.

a) The heave damping ratio increases by 50% and 100% for increase of disk diameter ratio from 1.0 to 1.2 and 1.0 to 1.5 respectively. The heave damping ratio also increases by 34% and 50% for increase of relative spacing 0.3 and 0.5 respectively.
b) In the experiments, over the most of the range considered, the heave responses were larger for the Spars with the smaller plates than for those with the larger plates. The heave RAO reduces by 33% for the disk diameter ratio of 1.3 and 37% for the disk diameter ratio of 1.5. This decrease in heave response is mainly due to increase in viscous damping but also to the fact that the increase in heave added mass leading to increase in heave natural period on the addition of the heave plate.
c) The recommended diameter of the heave plate in between 20% to 30% larger than the diameter of the Spar results in optimum hydrodynamic responses in surge, heave and pitch mode. For a disk diameter ratio of 1.3, the spacing between the plates will enhance both heave added mass and vortex shedding process. As the spacing increases, the heave added mass and vortex shedding process increases and beyond relative spacing equal to 0.4, both the entities will become independent of spacing between the heave plates.
d) A recommended relative spacing between the heave plates is 30% to 40% larger than the diameter of the Spar with heave plate of disk diameter ratio of 1.3 in order to achieve optimum surge, heave and pitch responses.

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