Research Journal of Applied Sciences, Engineering and Technology 7(24): 5249-5257, 2014
DOI:10.19026/rjaset.7.921
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: February 22, 2014 Accepted: April 09, 2014 Published: June 25, 2014

Research Article

Wave Forces on Linear Arrays of Rigid Vertical Circular Cylinders in Regular Waves

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Abstract: The present investigation aims to experimentally determine the variation of forces and force coefficients acting on circular cylinders, which are arranged in a linear array along the direction of the waves. Most commonly used structural and non-structural elements in the construction of offshore platforms are circular cylindrical members. In many cases, these members are found in very close neighbourhood of each other, thus modifying the surrounding flow and wave forces acting on them. Model tests were conducted in the wave tank on a maximum of four cylinders of the same diameter. A reasonable scale factor was chosen considering the pertinent factors such as water depth, wave generating capability and accuracy of measurements. The cylinders were installed inside the wave tank as vertical cantilevers fixed at the top. Wave forces acting on the cylinders were measured using special wave force sensors exclusively designed and fabricated for the present project, while the wave profiles were recorded using wave probes installed in the wave basin. The results confirmed the presence of a force shielding effect on the trailing cylinders by the leading cylinders with few exceptions. The findings also substantiated the significant modification of the forces on cylinders when they are present in a linear array. A common practice adopted for the design of offshore platforms was identified with a possibility of underestimating the wave forces acting on the cylindrical elements. In many cases, the experimentally computed hydrodynamic force coefficients were found to be lower than the standard values adopted by various design codes. These findings portray the significance of the present work in achieving economy in the design of jacket platforms and risers.

Keywords: Cylindrical members, force coefficients, jacket platform, linear array, regular wave, wave force

INTRODUCTION

The significant presence of shallow water oil reserves and the aging of existing oil production platforms have resulted in an increase in demand for new jacket platforms. This hike in demand and its high construction cost are demanding the engineers for a safe and optimum design, rather than a very conservative one as in practice. The very initial step towards achieving this goal is the accurate estimation of the forces on the structural members, risers and conductors of the platforms. The members of a platform are in constant interaction with the neighbouring members, causing inevitable variation in the wave forces acting on them. The design of offshore platforms shall be optimum when force variation, arising out of this flow interference, is also regarded as a design consideration.

A study on the wave forces acting on circular cylinders in regular waves at a constant water depth is made in the present paper. A maximum number of four cylinders, arranged in a linear array, are considered for the study. When an individual cylinder was tested in waves in the absence of any neighbouring cylinders, it was expected that the forces recorded on that cylinder would be higher than the forces acting on it tested in presence of neighbouring cylinders. In the present study, effort has been made to establish the presence of shielding effect in linear arrays of cylinders. The forces recorded on different cylinders in the array substantiated the possibility of the shielding effect being related to the position of the cylinders in the array. Thus a study on the variation of this shielding trend in regard of the cylinder's position in the linear array is also made and the conclusions are presented. A flaw in the design of jacket platforms, risers and conductors is also highlighted.

Many design codes recommend the minimum values to be used for drag and inertia coefficients in the Morison equation for estimating the wave forces on small diameter members. In most cases, the design engineers estimate the wave forces using these minimum values. These values are suggested without giving due consideration to the fact that the offshore platforms consist of a group of tubular cylinders such as risers and conductors which are constructed in close proximity with different arrangements, where the neighbouring pipes can significantly influence the hydrodynamic responses of a single isolated cylinder.

In this study, an effort is made to determine the hydrodynamic force coefficients for cylinders present in

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different linear array configurations. The force coefficients were computed from the Morison equation by making use of the experimentally recorded wave forces and wave profiles. Determination of optimum and safe wave loads on the structure is given primary focus rather than adopting the conventional conservative force estimation methods. The accurate values of force coefficients to be obtained are considered to give modifications in the design and dimensional parameters of the platforms which is deemed to enhance the economic feasibility of the big-budget offshore projects.

LITERATURE REVIEW

It is a common practice to ignore the flow interference effect in the hydrodynamic force calculation in the case of array of cylinders (Heideman and Sarpkaya, 1985). Comprehensive evaluation and review of the wave forces acting on single cylinders is given in Cotter and Chakrabarti (1984) and Williamson (1996). Some of the previous researches reported a force reduction trend on the trailing cylinders present in an array. This notion of shielding effect, namely a force reduction phenomenon, was given a mention in Sarpkaya (1979). But in the present study, investigation is made to find any trend in this shielding effect with respect to the position of the cylinders in the array.

Accurate determination of wave forces is very essential for the safe design of the structures to be installed in waves. This wave forces estimation could be made precise and optimum by using accurate force coefficients in the Morison equation. Prediction of these accurate coefficients is not an easy task. There is no single parameter with which the drag and inertia coefficients may be correlated without the need for other parameters, thus showing the complexity of the determination of hydrodynamic force coefficients (Shafieefar, 2001; Neill and Hinwood, 1998). Early works related to the estimation of darg and inertia coefficients were done by Chakrabarti (1981) and Sarpkaya (1979). Chakrabarti (1981) conducted a study in the wave basin to determine the hydrodynamic coefficients of a vertical cylinder and the results were compared with the findings presented by Sarpkaya (1979).

While many of the researches focused on the coefficient estimation on single cylinders, only very few focused on force coefficient estimation on cylinders present in arrays. From an experimental study of two separate cylinder configurations involving 3 circular cylinders in total (Prastianto *et al*., 2008) it is concluded that the change of linear spacing between the cylinders is having a very weak effect on the upstream cylinder but oppositely strong on the downstream cylinders. Recent experimental investigations on group of cylinders were carried out by Sparboom and Oumeraci (2006), Hildebrandt *et al*. (2008) and Bonakdar and Oumeraci (2012).

The values of hydrodynamic force coefficients to be adopted for design of offshore structures is given in design code practices such as API (2007), DNV (NORSOK Standard N-003, 2007) and PTS (2012).

Theoretical considerations:

Wave force calculation: Wave force estimation on small diameter members like the members of a jacket platform, is done using the well-known (Morison *et al*., 1950) equation. The Morison equation which gives the force on a unit length of a vertical cylinder is given in Eq. (1):

$$f = C_M \frac{\rho \pi D * D}{4} \dot{U} + C_D \frac{\rho\ D}{2} U\ |U| \quad (1)$$

where,

f = The force per unit length acting on the member
ρ = The water density
D = Cylinder diameter
$\dot{U}$, U = The water particle acceleration and velocity, respectively

Assuming that the cylinder extends from the ocean floor to the still water level, the total force on the cylinder is obtained by integrating Eq. (1) between the water depth limits and making necessary substitutions for the terms. The resulting equation is Eq. (2):

$$F = \rho\ g\ V\ \frac{H}{2d} \tanh (kd)$$
$$\left[C_M \sin\phi + C_D \frac{H}{4\ \pi\ D} \frac{2kd + \sinh 2kd}{\sinh kd * \sinh kd} \cos\phi\ |\cos\ \phi|\right] \quad (2)$$

where,

ρ = The water density
g = Acceleration due to gravity
V = The volume of cylinder under water
H = Wave height, d is water depth
k = Wave number
C_M and C_D = Inertia and drag coefficients
D = Cylinder diameter and ϕ is the phase angle

METHODOLOGY

Linear array configuration with one, two, three and four cylinders were considered in the present study. The wave forces acting on every cylinder is recorded using wave force sensors. These forces were plotted against the time period of the waves. Observation is made to find any trend in the variation of wave forces with respect to the position of the cylinder in the array considered. Wave force variation with wave heights and time periods is also studied.

The hydrodynamic force coefficients were estimated using numerical computation by adopting the most suitable combination of drag and inertia coefficient and phase angle, such that the deviation of the numerically computed wave forces at the peaks and the zero-crossing points, from the experimental forces, were minimal simultaneously. Equation (2) was made use for estimating the force coefficients. The drag and inertia coefficients thus obtained shall be plotted against the time periods of the waves. The scatter range of these coefficients is noted and compared with the standard values of these coefficients in the design codes.

Experimentation: A series of experiments were carried out in the wave basin of the Offshore Engineering Laboratory of Universiti Technologi PETRONAS (UTP), Perak, Malaysia. The wave basin is 22 m long, 10 m wide and 1.5 m deep. The wave maker system comprises of wave-maker, remote control unit and signal generation system. Other components that are integrated in the wave tank tests are the wave probes, strain gauges and the specially fabricated wave force sensors. The wave tank is equipped with multiple paddle wave-maker capable of generating regular and random waves. Dynamic wave absorbers are provided along the side opposite to the wave-maker, to minimize the reflection of waves from the wall behind. The wave basin is also equipped with three movable remote controlled bridge platforms to support testing personnel and equipments. Unidirectional, regular waves with maximum prototype wave height and maximum prototype time period of 8.25 m and 22.25 sec, respectively are studied. The wave tank facility of UTP is shown in Fig. 1.

The test specimens were galvanized iron cylindrical pipes of wet length 0.95 m and were of prototype diameter 2.31 m. Cylinders were installed inside the wave tank as cantilevers fixed at the top. All the cylinders were instrumented with a wave force sensor, which were designed exclusively for the present project. Design details of the load cell were published in an earlier paper (Idichandy, 2001). The benefit of these sensors over the conventional ones is that, the former has proved itself good for measuring wave forces acting on the entire length of the cylinder while the latter is capable of measuring only the axial force. The material properties of the fabricated wave force sensors are given in Table 1.

Fabricated wave force sensor of dimensions 0.10×0.05×0.03 m is shown in Fig. 2. It is provided with four screw holes at both the top and bottom faces for making necessary fittings. One face of the load cell is provided with four strain gauges, which again is connected to suitable data loggers for recording the wave forces.

For recording the wave profile, wave probes were deployed in the wave tank. The wave profiles recorded from these probes were used in the accurate estimation of the actually generated wave heights. It was found that the actually generated wave heights were in good agreement with the input wave height for wave generation, showing the accuracy of the measurement calibration adopted.

Fig. 1: Wave tank facility

Fig. 2: Wave force sensor mounted with strain gauges

Table 1: Material properties of wave force sensor

Material used	Aluminum-6061
Material property	Value
Mass density (kg/m^3)	2710
Yield strength (MPa)	275
Ultimate tensile strength (MPa)	310
Young's modulus (GPa)	68.90
Poisson's ratio	0.33
Shear modulus (GPa)	25.90

Table 2: Model and prototype wave characteristics

Model H (m)	Model T (sec)	Prototype H (m)	Prototype T (sec)
0.150	1.0	8.250	7.42
0.100	1.5	5.500	11.12
0.075	2.0	4.125	14.83
0.060	2.5	3.300	18.54
0.040	3.0	2.200	22.25

Knowing that, in the case of water flow with a free surface, the gravitational effects predominate, the Froude's scaling law was employed for the scaling of parameters (Chakrabarti, 1994). A scale of 1:55 was chosen considering the relevant factors such as, water depth, wave generating capability and accuracy of measurements. Wave forces were measured for the different wave heights and time periods, as given in Table 2. Five different wave heights were considered for the study. For each of these five wave heights, waves were generated with five different time periods and forces on all the cylinders were recorded. All the tests were conducted at a constant model water depth of 1 m.

In addition to the wave force measurements on a single cylinder, three other configurations as shown in Fig. 3 were also studied.

In these configurations, the cylinders were arranged in a linear array along the direction of the wave, the cylinder spacing (S) being three diameters between centres in all cases. The arrows show the direction of oncoming waves. The cylinders were successively placed one behind the other, along wave direction, to attain these configurations and each

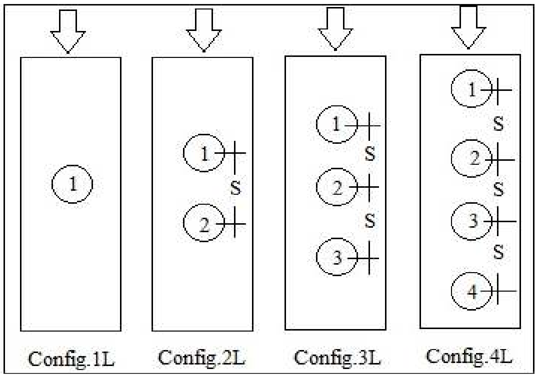

Fig. 3: Cylinder configurations

Fig. 4: Config.4L installed in wave tank

configuration was tested individually in waves. All the tests with two or more cylinders used the same flow settings as for the single cylinder. Hence for each run with more than one cylinder, there corresponded a single cylinder run with precisely the same external flow conditions. This facilitated the isolation of the interference effect due to the presence of neighbouring cylinders, by direct comparison of the forces. Figure 4 shows the Config.4L configuration, as installed in the wave basin for testing.

RESULTS AND DISCUSSION

Generally it was observed that, the wave forces acting on cylinders were modified in the presence of neighbouring cylinders. Keeping the time period and the cylinder diameter as a constant, when the wave heights were decreased, it was found that, the wave forces acting on the cylinders also decreased as shown in Table 3.

Table 3: Wave force ranges for different wave heights

Wave height (m)	Wave force range (kN)
8.250	332-123
5.500	181-66
4.125	134-49
3.300	112-34
2.200	71-26

The present study was carried out for five different wave heights and five different time periods and the wave forces acting on the cylinders are discussed for all the combination of above mentioned wave heights and time periods. However due to space limitation, the results for wave heights 8.25 and 3.3 m, only are presented in this study. Out of the different wave heights studied, 8.25 m is considered as a high wave height; 5.5 and 4.125 m are considered as middle range wave heights; 3.3 and 2.2 m as low range wave heights.

In Config.1L, where only a single cylinder (isolated cylinder) was tested in waves, for high wave height it was found that, the highest wave force was observed for a time period of 14.83 sec. For middle range wave heights, the highest wave force was noted for a time period of 7.42 sec and that for low range wave heights it was observed as 11.12 sec.

In Config.2L, for all the different wave heights considered, it was observed that, except for the highest time period considered, the leading cylinderis having a higher force than that acting on the trailing cylinder. This proves the existence of a type of shielding effect by the leading cylinder on the forces acting on the trailing one. The average hike in the wave forces on the 1st cylinder over the 2nd is 8%. The results for wave height 8.25 m is shown in Fig. 5 and 6.

In Config.3L it was found that, the wave forces on the 1st and the 3rd cylinders are very close to each other with a slightly higher force on the former cylinder. The force on the 2nd cylinder is always found to be smallest among that acting on the three cylinders, for all the corresponding wave heights and time periods, showing the effective hindrance on the wave forces by the leading cylinder. The rise in wave forces on the 3rd cylinder in comparison with the 2nd one shows that the hindrance effect is not directly related to the number of cylinders in front of the considered cylinder.

In Config.4L, four cylinders were linearly arranged and tested along the wave direction. When comparing the average wave forces over different time periods, the highest wave force among the four cylinders were always recorded on the 1st cylinder. Next highest wave force is recorded on the 3rd cylinder. For higher wave height, the forces on 2nd and 4th cylinder were found to be close to each other and are lower than that on the other two cylinders. For wave heights falling in the mid and low ranges, the lowest wave force is recorded on the 2nd cylinder. The results for wave height 3.3 m is shown in Fig. 7 and 8.

Comparison of the forces on single cylinder with that acting on cylinders in linear array: In comparing the forces on the cylinders in Config.1 L and Config.2 L, it was observed that, the forces acting on the leading cylinder of Config.2L is higher than that on the single cylinder in Config.1L by an average of 3%, while that on the trailing cylinder is lower by 5%. This is graphically shown in Fig. 5 and 7.

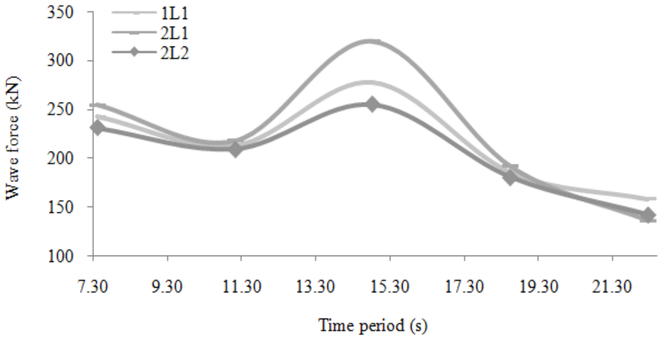

Fig. 5: Force variation for config.1L and 2L for H = 8.25 m

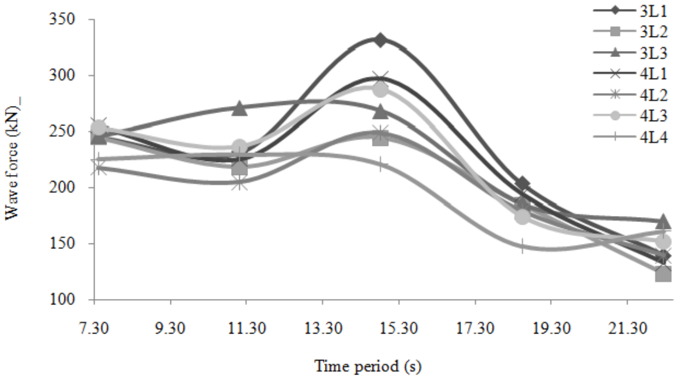

Fig. 6: Force variation for config.3L and 4L for H = 8.25 m

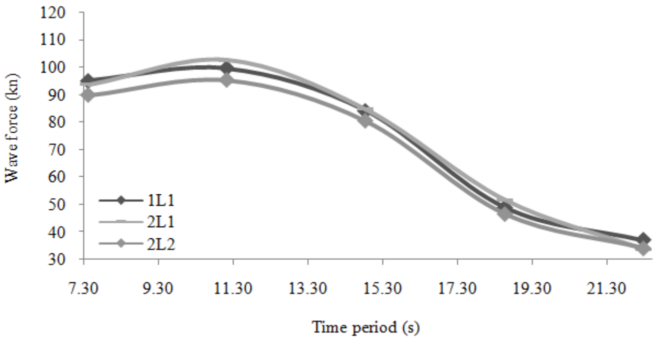

Fig. 7: Force variation for config.1L and 2L for H = 3.3 m

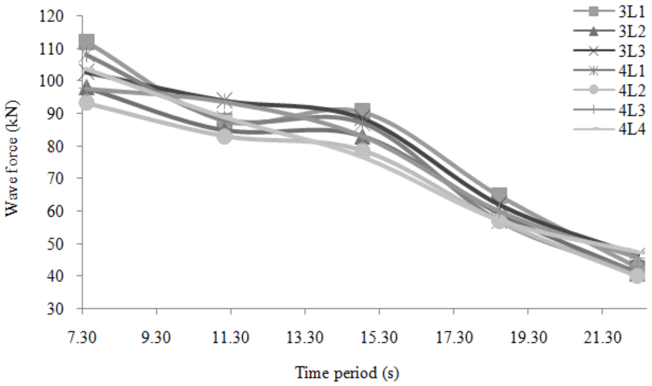

Fig. 8: Force variation for config.3L and 4L for H = 3.3 m

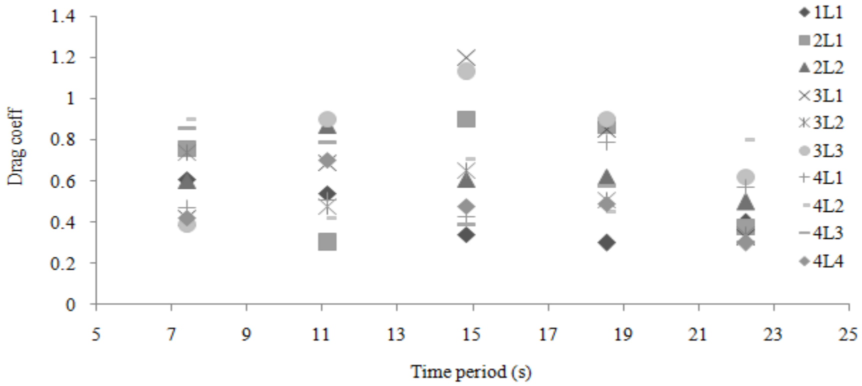

Fig. 9: Scatter of drag coefficients for H = 8.25 m

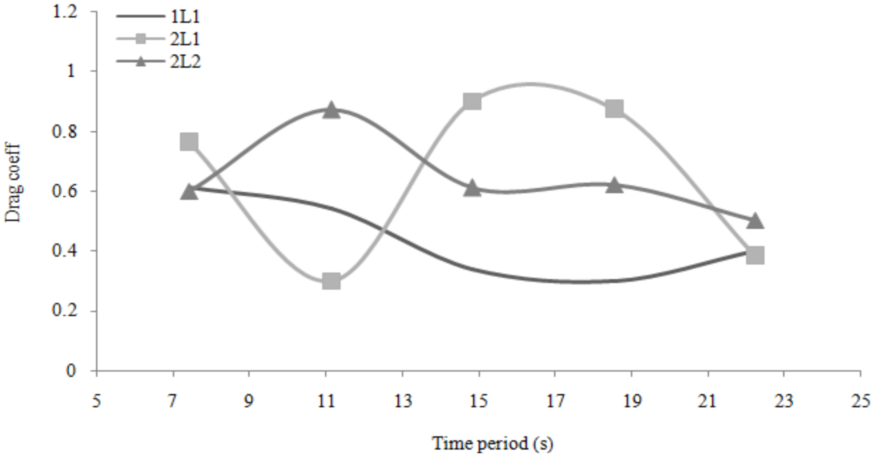

Fig. 10: Variation of Cd for config.1L and 2L at H = 8.25 m

For Config.3L and Config.4L, the forces on the 1st cylinder are by an average 8 and 4%, higher than that acting on the single cylinder in Config.1L. The forces on the 2nd cylinder are lower than that acting on the single cylinder in Config.1L except for low range wave heights. But when it comes to the 3rd cylinder in both these configurations, it was observed that the forces were comparable to the ones acting on the 1st cylinder in the corresponding configurations. Forces on 4th cylinder in Config.4L are showing a random trend in comparison with that acting on the single cylinder in Config.1L. Graphs for Config.3L and Config.4L are shown in Fig. 6 and 8.

The concept of, "isolated cylinder" model (Heideman and Sarpkaya, 1985), i.e., each cylinder in the array is modelled as an isolated cylinder and all individual cylinder forces are summed to get the total force on the array, is a very commonly adopted design practice in the offshore construction industry. Findings of this study question the validity of this concept. When the forces on the cylinders in the array are found to be greater than that acting on the "isolated cylinders", this leads to an underestimation of the forces and poses a severe threat to the safety and serviceability of the platforms as a whole or its members.

Variation of hydrodynamic force coefficients: For all the different wave heights and time periods considered, the drag coefficients are falling in the range of 0.3 to 1.2, with more than 60% of the values recorded, being lower than the specified minimum in the design code (PTS, 2012). The plot in Fig. 9 shows the scatter of these coefficients for a wave height of 8.25 m.

Figure 10 and 11 show the variation of these drag coefficients on different pipes in the different cylinder configurations considered.

As can be seen from these plots, no particular trend is observed in the variation of the drag coefficients in regard to the position of the cylinders in the different cylinder configurations studied. This high randomness in the nature of drag coefficients, indicate the strong influence of wave heights and time periods considered.

For all the different wave heights and time periods considered, the inertia coefficients are falling in the range of 1.0 to 2.5, with almost 90% of the values recorded, being lower than the specified minimum in the design code. The scatter plot of the inertia

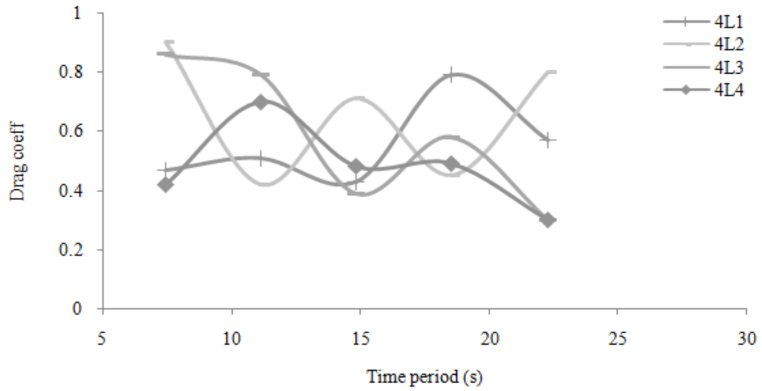

Fig. 11: Variation of Cd for config.4L at H = 8.25 m

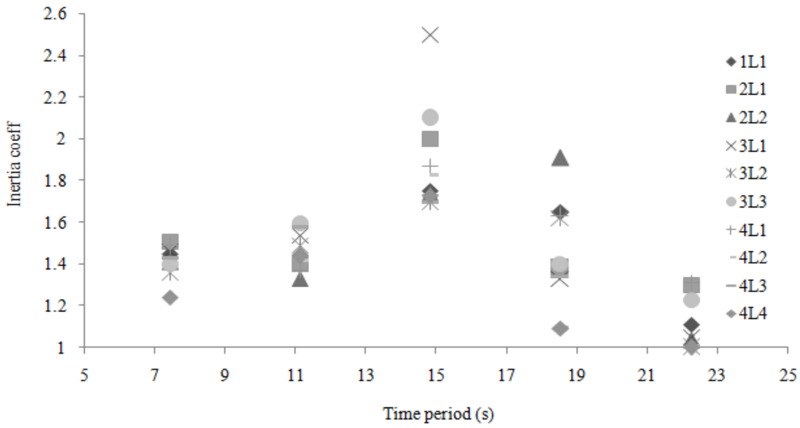

Fig. 12: Scatter of inertia coefficients for H = 8.25 m

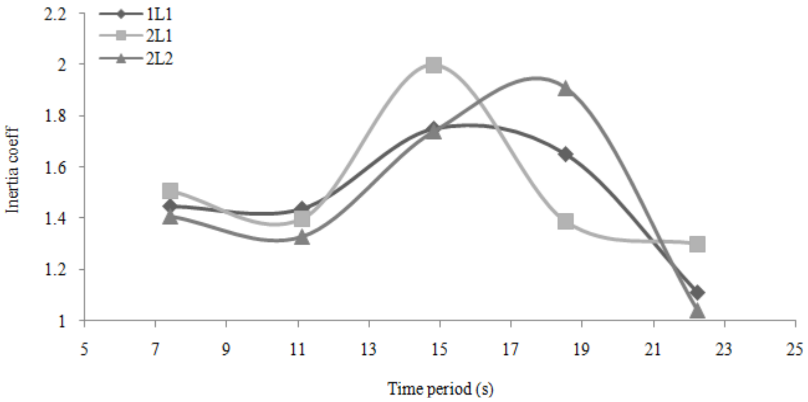

Fig. 13: Variation of Cm for config.1L and 2L at H = 8.25 m

coefficient values for wave height 8.25 m is given in Fig. 12.

Figure 13 and 14 show the variation of these inertia coefficients on different pipes in the different cylinder configurations considered.

From the above two plots it can be seen that, unlike the random variation of drag coefficients, in majority of the cases, a peak was observed in the values of inertia coefficients at a time period of 14.8 sec. This is shown in Fig. 13 and 14, for a wave height of 8.25 m.

The minimum values of drag and inertia coefficients specified by different design standards are given in Table 4. Majority of the experimentally computed force coefficients were lower than these recommended values. This fact point towards a possibility of attaining an economically favorable and optimum design of jacket platforms, risers and conductors that could be achieved with the use of experimentally estimated coefficients.

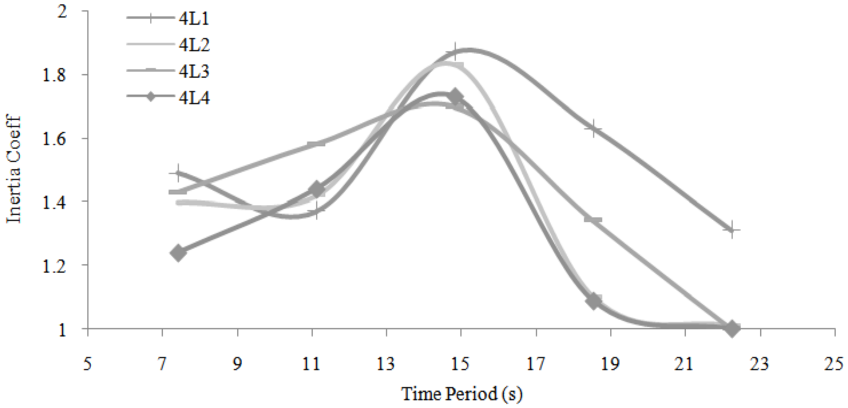

Fig. 14: Variation of Cm for config. 4L at H = 8.25 m

Table 4: Recommended force coefficients by design codes

Code	Drag coefficient	Inertia coefficient
PTS	0.65	1.6
API	0.60-1.00	1.5-2
DNV	0.70-1.20	2

CONCLUSION

The major conclusions of the study are given here. For all the cylinder configurations studied, it was found that:

- The leading cylinder is experiencing the highest average wave force.
- Force shielding effect was eminent on the cylinder immediately preceding the leading one. In the four cylinder configuration, shielding effect was noted on the last cylinder as well.
- The concept of "isolated cylinder" model is questioned and the need of accurate estimation of wave forces on the members is recognized.
- The variation of drag coefficient with time period is random in nature while that of inertia coefficient shows an observable pattern.
- Majority of the experimentally computed drag and inertia coefficient values are lower than the minimum values recommended for use, by various design standards.

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