Experimental Investigation of Hydrodynamic Forces on Rigid Vertical Cylinders in Regular Waves

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***Abstract*—The predominant aspect of interest, presented in this study is the influence of wave heights and cylinder diameters on the wave forces acting on cylindrical members. The effects on the wave forces due to the interactions between the adjacent cylindrical members are also presented. Model tests were conducted in the wave tank, on cylinders of four different diameters with wave characteristics pertaining to three major offshore sites of Malaysia. This particular paper, however, is limited to a discussion on rigid, vertical cylinders in regular waves. In the studied cases of wave heights and cylinder diameters, it was observed that the variation of cylinder diameters is having a prominent effect on the wave forces rather than the variation in wave height. The results also depict that the proximity of other members significantly affect the wave forces on the considered member. The primary area of application is intended to be the design of jacket type platforms, risers and conductors.**

Keywords — wave forces; wave height; cylinder diameter; regular waves; proximity

I. Introduction

Among the vast expanse of structural analysis considerations needed for the design of offshore structures, the most significant aspect is the effect of ocean wave loads. All the characteristics and parameters of the actual ocean waves are time dependent and varying. Owing to the highly nondeterministic and unpredictable characteristics of the waves, the wave load estimation on structures are to be done with utmost concern and caution and for that reason itself a very detailed study of these wave loads have to be made for assessing the reliability and safety of offshore structures.

The cylindrical structures find numerous applications in the offshore edifice in comparison with the square and rectangular sections, which could easily be fabricated. This is attributed to the phenomena of narrow wake development and low vortex shedding around the circular cylindrical bodies resulting in a lower wave force on the structure [1]. Wave force estimation on small diameter cylindrical structures is done by making use of the well-known Morison equation, presented in [2]. The initial works on the experimental determination of wave forces are presented in [3]. The dependence of the wave forces acting on a single circular cylinder in wavy and harmonic flows on the Reynolds number, Keulegan-Carpenter number, and the relative roughness ratio has been clearly established in [4] and [5]. Extensive appraisal of flow around single cylinders is given in [6]. Comprehensive evaluation and review of the wave forces around multiple cylindrical pipes are furnished by works presented in [7] and [8]. The wave characteristics and the hydrodynamic force coefficients to be used in the theoretical wave force calculation were obtained from [9].

The conventional practice of design of offshore structures, only considers the theoretical calculation of wave forces using the Morison equation, employing the drag as well as the inertia coefficient. The experimental results suggest that the site-specific experimental determination, rather than the theoretical estimation, of wave forces is inevitable for the accurate design of the structural members. In the present study, regular wave characteristics pertaining to three Malaysian offshore locations are considered and the variation of wave forces acting on the cylindrical members for these wave characteristics are investigated.

A. Wave force calculation

The in-line wave forces on small diameter cylinders are estimated theoretically using the well-known Morison equation. The total force is composed of drag as well as inertia part as given in (1). The influence of various wave and prototype parameters on the drag and inertia coefficients are significant and plays an important role in the estimation of accurate wave forces acting on the structure.

$$F_T = 1/2\ \rho\ D\ u\ |u|\ C_d + \pi/4\ \rho\ D^2\ \alpha\ C_m \quad (1)$$

Where

F_T = Total wave force
ρ = Density of sea water
D = Cylinder diameter
u = Horizontal water particle velocity
α = Horizontal water particle acceleration
C_d = Drag coefficient
C_m = Inertia coefficient

B. Modelling criteria and Scaling

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 [10]. A scale of 1:50 (1:λ) was chosen considering the relevant factors such as, water depth, wave generating capability and accuracy of measurements.

The common variables found in study of wave mechanics are identified and using Froude's law and the scale factor λ, the suitable multipliers to be used to obtain the prototype parameters from the model data are shown in Table I.

TABLE I. SCALE FACTOR MULTIPLIERS

Variable	Unit	Scale factor
Wave Height	L	λ
Wave Period	T	$\sqrt{\lambda}$
Wave Force	$ML\,T^{-2}$	λ^3
Wave Length	L	λ
Particle Velocity	$L\,T^{-1}$	$\sqrt{\lambda}$
Particle Acceleration	$L\,T^{-2}$	1

II. EQUIPMENTS AND METHODOLOGY

The experimental determination of wave forces on the model cylinder specimens are made by conducting wave tank tests for different site-specific wave characteristics.

A. Load Cells

Since the wave forces acting on the model test cylinders are of less magnitude, very sensitive and accurate load cells were designed and fabricated exclusively for the present study. The design details of the load cell were published in an earlier paper [11]. The material properties of the fabricated load cells are given in Table II.

TABLE II. MATERIAL PROPERTIES OF FABRICATED LOAD CELL

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)	68.9
Poisson's Ratio	0.33
Shear Modulus (GPa)	25.9

Fabricated load cells of dimensions 0.10 m X 0.05 m X 0.03 m is shown in Fig. 1. It is provided with four screw holes at both the top and bottom faces for the purpose of bolting cross-beams and the test cylinders. One face of the load cell is provided with four strain gauges, which again is connected to suitable data loggers for the recording of wave forces.

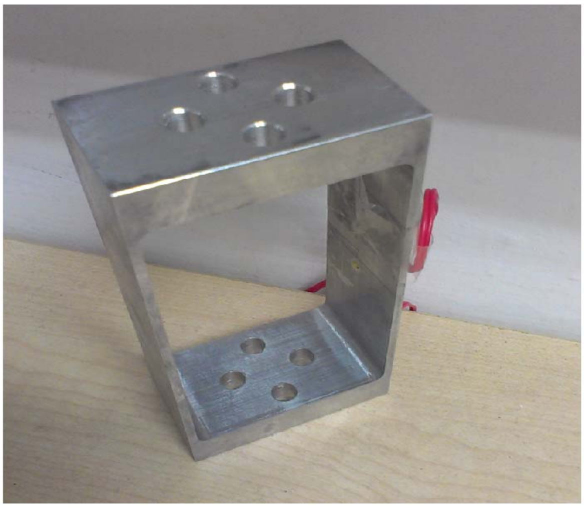

Fig. 1. Fabricated load cell

B. Wave Tank and Model Cylinder Specifications

Model tests were performed in the wave tank of Universiti Teknologi PETRONAS, Perak, Malaysia, which is 22m long, 10m wide and 1.5m deep. The wave generator consists of sixteen individual paddles that could generate waves propagating in different directions. Other components that are integrated in the wave tank tests are the wave probes, strain gauges and the specially fabricated load cells. Unidirectional, regular waves with maximum model wave height and maximum model time period of 0.17 m and 1.27 s respectively are studied. The wave tank facility of UTP is shown in Fig.2.

Fig. 2. Wave tank facilities - Wave generator

The test specimens are cylindrical pipes of wet length 0.95 m, made from standard polyvinyl chloride (PVC), with specifications as given in Table III.

TABLE III. CYLINDER SPECIFICATIOS

Specification	Value	
	Model diameter	***Prototype diameter***
Diameters used (m)	0.026	1.3
	0.032	1.6
	0.042	2.1
	0.048	2.4

Wave characteristics pertaining to Peninsular Malaysia Operation, Balingian basin and Baram Delta are considered for the present study and are given in Table IV. A scaled water depth of 50 m is used at all locations for the study.

TABLE IV. MODEL & PROTOTYPE WAVE CHARACTERISTICS

Model Wave Height (m)	Prototype wave height (m)	Model Time period (S)	Prototype Time period (S)
0.169	8.44	1.18	8.34
0.130	6.5	1.26	8.90
0.116	5.8	1.27	8.98

To find the influence of wave heights and cylinder diameters on the wave forces on the offshore structural members, four cylinders with specifications as presented in Table III are used. Wave forces on each of the cylinders are recorded individually corresponding to the three of the wave characteristics as given in Table IV.

Furthermore, to study the variation of wave forces on the structures due to the presence of another member in its proximity, a tandem cylinder configuration with two cylinders of the same diameters as shown in Fig. 3 is studied. The wave forces on each of the cylinders were recorded. In both the cases of individual & multiple cylinders, the rms value of the prototype wave forces are tabulated along with the cylinder diameters and the wave heights as well.

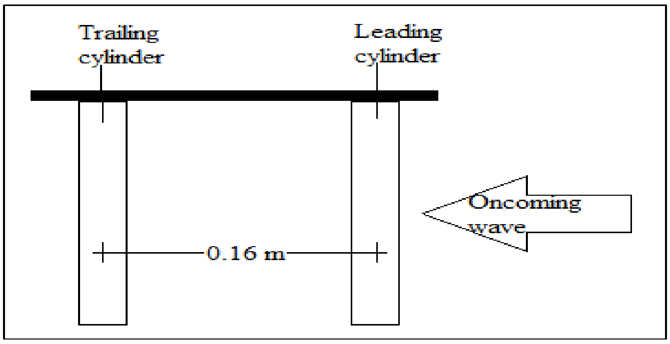

Fig. 3. Two-cylinder configuration

III. RESULTS AND DISCUSSION

In this section, the linear response of the specially fabricated load cells is presented at the outset. A comparison of the experimental and theoretical wave forces are furnished thereafter. The variations of wave forces (root mean square value) with change in wave heights and cylinder diameters are endowed. Also, the influence of the presence of a cylinder in proximity to another, on the wave forces are studied and presented.

A. Linear response of the fabricated load cell

Specially fabricated load cells are used for the wave force measurements. Calibration of the load cells were done by applying loads of magnitude 5 N and 15 N. The linear relation of the recoded forces, as shown in Fig. 4, with the actual applied loads depicts the flawless design and fabrication of the used load cells.

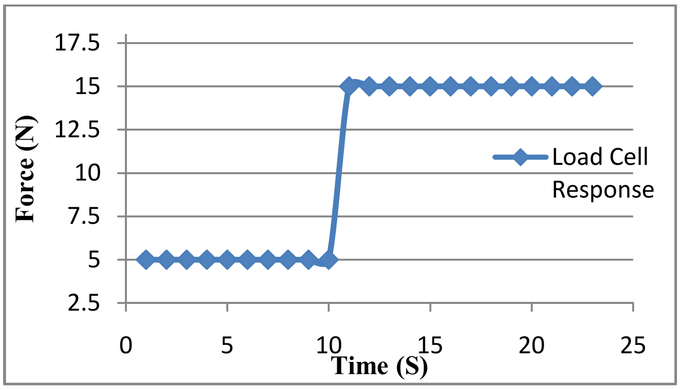

Fig. 4. Linear response of fabricated load cell

B. Experimental and theoretical wave force comparison

A comparison of the theoretical and experimental time series of the wave force variation at a wave height H = 5.8 m for D = 2.1 m, is as shown in Fig. 5. As can be clearly observed from the plot, the theoretical force calculation is greatly over predicting the actual wave forces. In the present case considered, the theoretical force calculation resulted in an average of 80 kN extra load on the single cylinder considered, depicting the significance of site specific experimental wave force estimation.

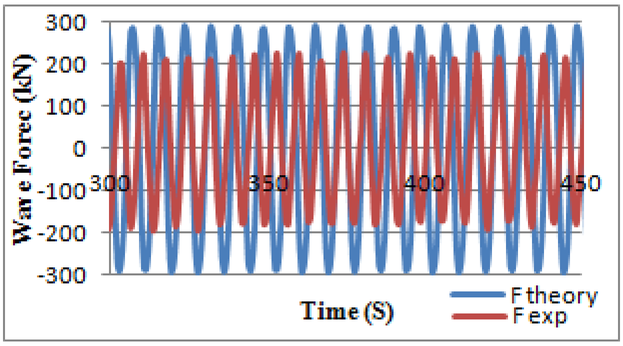

Fig. 5. Force time series

C. Variation of wave forces with wave heights

- *Individual cylinders*

Cylinders of prototype diameter, D = 2.1 m & 2.4 m, were tested in waves, individually (one at a time). The rms values of the forces acting on the cylinders are tabulated in Table V.

TABLE V. WAVE FORCE VARIATION FOR SINGLE CYLINDER

Wave Height (m)	Wave force (kN) acting on:	
	D = 2.1 m	*D = 2.4 m*
8.44	266.0	403.9
6.5	228.6	355.6
5.8	210.6	301.7

These forces were plotted against the wave heights pertaining to each location (Fig.6). There is an increasing trend for the wave forces recorded on both the cylinders with the increase in the wave heights, as shown in Fig. 6. An increase in wave force of 34% for D = 2.4 m and 26% for D = 2.1 m is recorded when wave heights was increased from 5.8 m to 8.44 m.

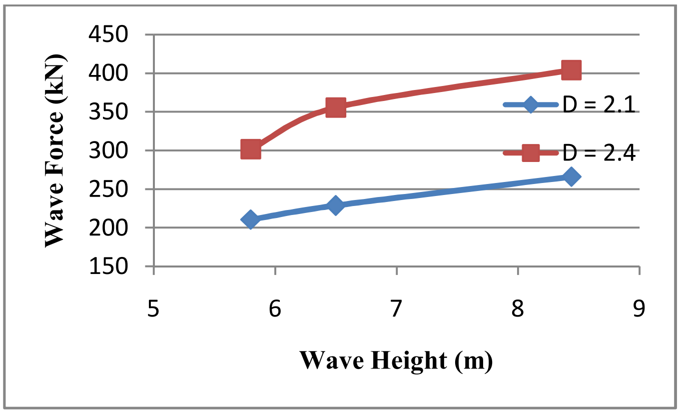

Fig. 6. Variation of wave forces with wave heights

- *Multiple cylinders*

A cylinder configuration as shown in Fig. 3 is studied. The wave forces acting on leading as well as trailing cylinders for the two diameters considered are given in Table VI.

TABLE VI. WAVE FORCE VARIATION FOR MULTIPLE CYLINDERS

Wave Height (m)	Wave force (kN) acting on D = 2.1 m:		Wave force (kN) acting on D = 2.4 m:	
	Leading Cylinder	*Trailing Cylinder*	*Leading Cylinder*	*Trailing Cylinder*
8.44	222.5	222.0	375.5	389.5
6.5	184.2	193.8	370.0	394.6
5.8	163.0	172.8	313.8	335.6

For a given wave height, the wave forces recorded on both the leading as well as trailing cylinders were close to each other with a maximum variation of 7%, as can be observed from the tabulated data.

For D = 2.1 m, the wave force on leading cylinder increases by 37% & that on trailing cylinders increases by 29%, when wave height was increased from 5.8 m to 8.44 m. Corresponding increases in the wave forces were 20 % and 16% in the case of D = 2.4 m. The variation of wave forces with wave heights, on the cylinders in the studied configuration is given in Fig. 7 and Fig. 8.

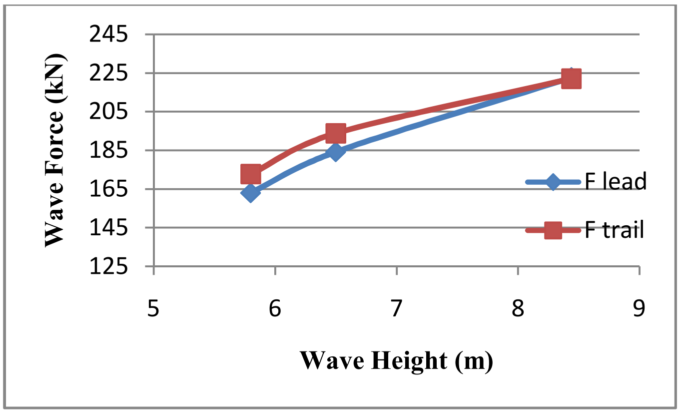

Fig. 7. Variation of wave forces on leading & trailing cylinders with wave heights, for D=2.1m

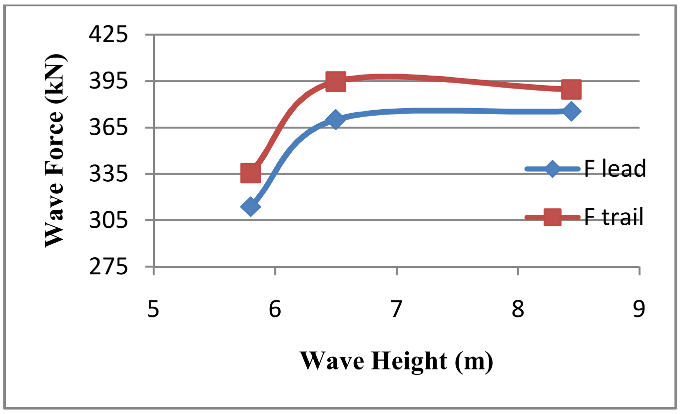

Fig. 8. Variation of wave forces on leading & trailing cylinders with wave heights, for D=2.4m

D. Variation of wave forces with cylinder diameters

- *Individual cylinders*

The wave forces acting on cylinder with D = 1.6 m is greater than that acting on the cylinder with D = 1.3 m for all the wave heights considered. The wave forces acting on both the cylinder diameters for different wave heights considered are given in Table VII.

Also, it was found that the percentage increase in wave force is the highest for a wave height of 8.44 m, when cylinder diameter is increased from D = 1.3 m to D = 1.6 m as tabulated below.

TABLE VII. WAVE FORCE VARIATION FOR SINGLE CYLINDERS

Wave Height (m)	Wave Force (kN) on :		Increase in wave force (%)
	D = 1.3 m	***D = 1.6 m***	
8.44	149.77	208.4	39.15
6.5	135.59	183.5	35.33
5.8	104.07	136.2	30.87

- *Multiple cylinders*

The variations of wave forces acting on the leading as well as the trailing cylinders are presented in Table VIII and Table IX. The percentage increase of the forces with the increase in diameter is also presented.

TABLE VIII. WAVE FORCE VARIATION FOR LEADING CYLINDERS

Wave Height (m)	Wave Force (kN) on leading cylinder :		Increase in wave force (%)
	D = 1.3 m	***D = 1.6 m***	
8.44	125.1	195.5	56.28
6.5	118.7	187.3	57.79
5.8	98.1	156.9	59.94

TABLE IX. WAVE FORCE VARIATION FOR TRAILING CYLINDERS

Wave Height (m)	Wave Force (kN) on trailing cylinder :		Increase in wave force (%)
	D = 1.3 m	***D = 1.6 m***	
8.44	140.2	197.6	40.94
6.5	119.2	195.8	64.26
5.8	101.4	170.5	68.14

From the data presented in Table VII, Table VIII and Table IX, it was found that a maximum increase of 68% and a minimum increase of 31% were observed in the wave forces when the diameter was changed from D = 1.3 m to D = 1.6m. From Table V and Table VI, the corresponding increases when the diameter were changed from D = 2.1 m to D = 2.4 m were calculated as, 104% and 43%. Combining the data from all the tabulations made, it can be observed that a maximum increase of 231% and a minimum increase of 162% were observed in the wave forces when the diameter was changed from D = 1.3 m to D = 2.4 m.

With the increase of cylinder diameter from 1.3 m to 1.6 m, the average wave force on the leading cylinder increases by 58% and that on the trailing cylinder increases by 56%. It should be noted that the corresponding force increase for the single cylinders was only 36%, showing the existence of neighboring cylinders significantly modifies the wave forces.

IV. CONCLUSIONS

The study reported in this paper is a part of an investigation for the determination of site-specific hydrodynamic force coefficients to be used in the Morison equation. The major conclusions emerged from the present study are:

- The theoretical calculation overestimates the wave force values on the cylinders in comparison with the experimental wave forces.
- For the range of wave heights and cylinder diameters considered, the variation of diameters is having a greater effect on the wave forces rather than the variation of wave heights.
- The presence of neighboring cylinders significantly modifies the wave forces acting on the cylinders.
- In the two-cylinder configuration studied, the wave forces acting on the leading as well as the trailing cylinder are close to each other, for a given diameter, when the wave heights are varied.

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