

Experimental Investigation of Hydrodynamic Coefficients for Short-Crested Waves

Ng Cheng Yee*, Siti Nor Adha Binti Tuhaijan and Ligar A. Pangestu

Department of Civil and Environmental Engineering, University Technology PETRONAS, 32610 Seri Iskandar, Perak Malaysia; chengyee.ng@utp.edu.my, ctnodeha@gmail.com, ligarapangestu@gmail.com

Abstract

Objectives: To determine the hydrodynamic coefficients; drag (Cd) and inertia (Cm), for short-crested waves exerted on vertical cylinder. **Methods/Statistical Analysis:** An experimental study on hydrodynamic coefficients of the top-fitted vertical cylinder subjected to short-crested waves is presented. The model tests were carried out in the wave tank of Offshore Laboratory of University Technology PETRONAS, Malaysia. In this study, the model test was conducted by using two sets of vertical cylinder with diameter, 16 mm and 48 mm, which were subjected to four series of short-crested waves based on four different locations in Malaysian offshore region. The wave forces acting on the cylinder were recorded by using wave force sensor. The post processing data was carried out by considering The Least Square Method. The results were compared with the existing recommended hydrodynamic coefficients in the PETRONAS Technical Standard (PTS). **Findings:** The hydrodynamic coefficients for short-crested wave of a vertical cylinder were obtained. The results showed that the experimental hydrodynamic coefficient values are 30 % to 45 % lower than the recommended hydrodynamic coefficients provided in PTS. **Application/Improvements:** The hydrodynamic coefficients values obtained from this experimental investigation have ensured the possibility of designing an economical and optimum design of offshore platforms could be achieved.

Keywords: Drag Coefficient, Inertia Coefficient, Short-Crested Wave

1. Introduction

In Malaysia, oil and gas industry has contributed 20 % to the total of national income. Cost optimization becomes more critical since the oil price drastically dropped at the end of 2014. Hence, new innovation is required to improve the current technology, which may improve the cost optimization. The determination of the wave forces is an important step in the design stage of the offshore structure¹. A deep understanding of the wave-structure interaction is essential and it plays an important role in the wave force analysis.

In Malaysia, majority of the offshore structures are installed in the open sea and exposed to the short-crested wave's environment. The prediction of this type of wave is always neglected due to the existing wave force

formulation focused only the long-crested wave. Unlike short-crested wave, which the properties are complicated, long-crested waves are much simpler and ease to be adopted. By ignoring the properties of the short-crested waves, the design of the offshore structures might be overestimated. Hence, it was recommended that in the wave forces determination, short-crested wave has to be taken into consideration instead of long-crested wave in order to represent the real sea condition².

In order to estimate the wave forces on a fixed structure, an appropriate wave theory has to be selected. There are three different ways to calculate the wave force¹ which are Morison equation, diffraction theory, and also Froude-Krylov theory. For a small structure, Morison equation is likely to be used in the wave force calculation and this equation assumes to be composed of inertia and drag forces.

* Author for correspondence

The components consist of two hydrodynamic coefficients which are inertia and drag coefficients, and both must be experimentally determined. However, Morison equation has its limitation³ as the original equation cannot fulfill all the structural and environmental conditions, and to overcome this limitation, various investigations were carried out to modify the Morison equation to suit their structural and environmental conditions by determining the hydrodynamic coefficients⁴⁻⁶. Yet, from these previous researches, the researchers were only considering regular and random long-crested wave in the wave force analysis. Hence, a modified Morison equation should be developed in order to incorporate the effect of short-crested wave. In this paper, an experimental investigation to determine the hydrodynamic coefficients for short-crested wave was conducted and the findings were presented and discussed.

2. Methodology

2.1 Experimental Investigation

The purpose of this study is to determine the hydrodynamic coefficients for short-crested wave. In order to achieve this objective, an experimental investigation was carried out in the wave tank of the Offshore Engineering Laboratory of University Technology PETRONAS (UTP), Malaysia. This wave tank is equipped with the wave maker system, the fixed wave absorber, and the movable remote control mobile platform. The details of the wave tank facility as shown in Figure 1.

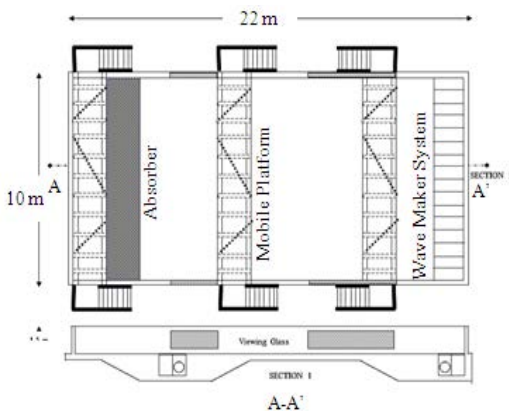


Figure 1. Wave tank details.

In this study, two sets of vertical cylinder with diameter 16mm and 48mm were considered. These models were made of galvanized steel, and had been arranged to form a cantilever beam by fitted the top. Figure 2 shows the model setup of model with a total wet length of $L=960\text{mm}$ and a wall thickness of $t = 2\text{mm}$. The model was instrumented with a waveforce sensor to measure the total wave force acting on the cylinder⁷⁻⁹. The sensor was installed with four strain gauges, which connected to the data loggers to record the wave forces. Detail of the wave force sensor is illustrated in Figure 3. The material properties of the wave force sensor are given in Table 1.

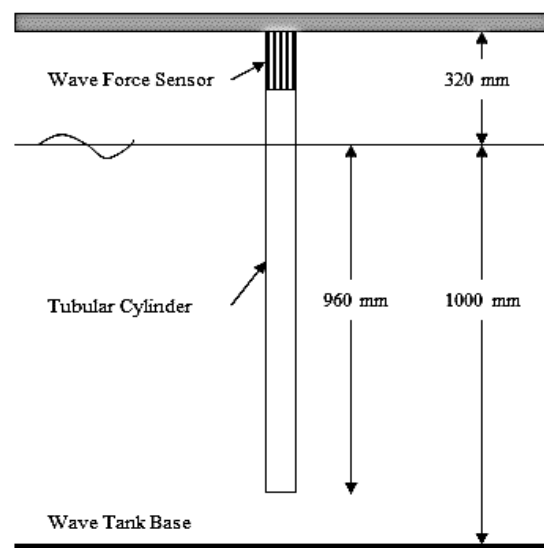


Figure 2. Model setup.

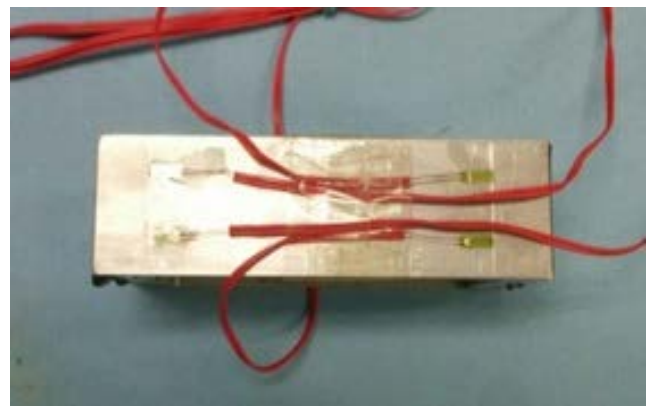


Figure 3. Wave force sensor.

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

Table 2 presents the details of the wave characteristics generated and the corresponding full-scale prototype wave parameters in accordance with Froude scaling law¹⁰. Four different locations in Malaysian offshore region¹¹; Peninsular Malaysia Operation (L1), Baram Delta (L2), Semarang (L3), and Erb West (L4), were considered. The scales were chosen based on the water depth of specified locations considering the relevant factors such as the wave generating capability and the accuracy of the measurements.

These waves were generated and the wave forces exerted on the model were measured and recorded for different wave height and time period.

Table 2. Model and prototype wave characteristics

L	Model			Prototype		
	Wave Period (s)	H(m)	Water Depth (m)	Wave Period (s)	H(m)	Water Depth (m)
L1	1.00	0.12	1.00	8.37	8.47	70
L2	1.03	0.09	1.00	8.92	6.53	75
L3	1.33	0.14	1.00	9.40	6.90	50
L4	1.00	0.11	1.00	7.87	6.70	62

2.2 Theoretical Considerations

The data measured from the experimental work were post process then to determine the hydrodynamic coefficient. The determination of the hydrodynamic force is very challenging. Morison equation is widely used to estimate the hydrodynamic force on tubular cylinder when exerted by waves¹². Generally, the long-crested wave has been considered in this equation. The total wave force was given as a summation of the drag and inertia components:

$$F_T = \frac{1}{2} \rho C_d D |u|u + \frac{\pi}{4} \rho C_m D^2 \dot{u} \tag{1}$$

where F_T = total wave force, ρ = density of sea water, D = diameter of cylinder, u = horizontal water particle velocity, \dot{u} = horizontal water particle acceleration, C_d = drag coefficient, and C_m = inertia coefficient.

The hydrodynamic force coefficients for short-crested wave were estimated by using the Least Squares Method for force time series, since it was found to be the most straight forward method by minimizing the square of the difference between the time series of measured and targeted forces¹³. The measured data by using the wave force sensor were analyzed and the estimated C_m and C_d are given as:

where T_n^I and T_n^D = quantities in the inertia and drag parts of Morison equation except the coefficients at every increment in a wave cycle ($n = 1 \dots N$) and f_n = respected wave force value at n time.

$$C_M = \frac{\sum f_n T_n^I \sum (T_n^D)^2 - \sum f_n T_n^D \sum T_n^I T_n^D}{\sum (T_n^I)^2 \sum (T_n^D)^2 - \sum (T_n^I T_n^D)^2} \tag{2}$$

$$C_D = \frac{\sum f_n T_n^D \sum (T_n^D)^2 - \sum f_n T_n^I \sum T_n^I T_n^D}{\sum (T_n^I)^2 \sum (T_n^D)^2 - \sum (T_n^I T_n^D)^2} \tag{3}$$

$$T_n^I = \frac{1}{2} \rho D |u|u \tag{4}$$

$$T_n^D = \frac{\pi}{4} \rho D^2 \dot{u} \tag{5}$$

3. Results and Discussion

In the following paragraphs, the hydrodynamic coefficients for short-crested wave represented. Both models; i.e. 16mm and 48mm diameter of vertical cylinders, were discussed separately.

3.1 C_m and C_d Values for Short-Crested Wave on 16 mm and 48 mm Vertical Cylinders

Table 3 shows the summary of C_m and C_d values for short-crested wave of vertical cylinder with diameter of 16 mm based on four different locations. These results were compared to the C_m and C_d values recommended by Petronas Technical Standard (PTS)¹³. As stated in PTS, the C_m and C_d values are 1.60 and 0.65 respectively. The percentage of difference between the experimental results and PTS values are tabulated in Table 4.

Table 3. C_m and C_d values for vertical cylinder 16 mm diameters

Location	C_m	C_d
L1	1.00	0.42
L2	0.92	0.43
L3	1.09	0.39
L4	1.04	0.40

Table 4. Percentage difference for the hydrodynamic coefficients measured for vertical cylinder 16 mm diameter as compared to PTS

Location	$C_m(\%)$	$C_d(\%)$
L1	37.5	35.4
L2	42.5	33.9
L3	31.9	40.0
L4	35.0	38.5

The C_m and C_d values for short-crested wave of vertical cylinder with diameter of 48 mm based on the four different locations are summarized in Table 5. For comparison purposes, the percentage of reduction between the experimental and PTS values is tabulated in Table 6.

Table 5. C_m and C_d values for vertical cylinder 48 mm diameters

Location	C_m	C_d
L1	1.03	0.47
L2	1.02	0.45
L3	1.10	0.50
L4	1.01	0.46

Table 6. Percentage difference for the hydrodynamic coefficients measured for vertical cylinder 48 mm diameter as compared to PTS

Location	$C_m(\%)$	$C_d(\%)$
L1	35.6	27.7
L2	36.3	30.8
L3	31.3	23.1
L4	36.9	29.2

The C_m and C_d values from PTS were obtained from an experimental investigation by considering only the

long-crested wave. As compared to the one measured in this study, it could be observed that the C_m and C_d values from PTS are generally greater for both models. This is mainly due to the assumption when the platform stretch is subjected to the maximum long-crested wave, the effect will be extended to all the stretch of the platform. On the other hand, as the short-crested waves, which propagated from different angle, hit the structure, very likely that the net effect will be lesser. Further in detail that drag force is associated with a pressure behind a body. For the long-crested wave condition, the low pressure region occurs behind the structure due to the fluid separation, and it leads to the force acting in the direction of the velocity. As the structure is subjected to short-crested wave, the low pressure region is less compared to the long-crested wave, due to the reduced wave velocity, as the effect of the various wave propagation. This resulting reduction in both the drag force and the C_d value. Whilst, the inertia force involves the momentum carried by the moving water particles, whereby as the flow passes around a structure, the water particles are having acceleration changes. In long-crested wave condition, the momentum will be higher due to the greater force exerted on the structure in one direction. Hence, the momentum would be smaller in the case of short-crested waves as the net effect of the wave accelerations from different angle would be less. In contrary to this, the inertia force and the C_m value were found reducing. By considering the measured C_m and C_d values, the overestimation of the wave forces acting on the offshore structure may be avoided. The above investigation indicated the effectiveness of the short-crested wave's effect, which significantly influences the hydrodynamic coefficients. These results have ensured the possibility of designing an economical and optimum design of offshore platforms could be achieved.

4. Conclusion

Experimental investigation was conducted in the wave tank in University Technology PETRONAS, Perak, Malaysia to determine the hydrodynamic coefficients for short-crested waves. In this study, two sets of vertical cylinder with different diameter had been used. Each model was subjected to four series of short-crested wave, by referring to four different locations in Malaysian offshore region. The results obtained were compared with

the hydrodynamic coefficients values specified in PTS. From this study, the following conclusions can be drawn:

- The hydrodynamic coefficients for short-crested wave of both vertical cylinders (16 mm and 48 mm) were varied for all locations (L1, L2, L3, and L4) and the values were obtained.
- Smaller hydrodynamic coefficients for short-crested waves were obtained as compared to the one by PTS. The percentage of reduction about 37 %, and 30 % for 16 mm and 48 mm diameter of vertical cylinder respectively were determined. The reduction of the hydrodynamic coefficients indicated that by considering short-crested wave, the effect of the net wave loading will be lesser as compared to the long-crested wave.
- Overall, it is proven that the hydrodynamic coefficients for short-crested wave shall be considered in the design stage of the offshore structures, for more economical structures.

5. Acknowledgement

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