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Effects of Marine Growth on Hydrodynamic Coefficients of Rigid Tubular Cylinders

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Abstract. In this paper the wave induced hydrodynamic forces and the corresponding hydrodynamic coefficients for a 42 mm diameter model pipe subjected to regular waves was investigated experimentally and the results were compared with the responses of a similar rigid cylinder fitted with marine growth. The main objective of this study was to quantify the effects of marine growth on the hydrodynamic forces experimentally and determine the associated hydrodynamic coefficients. The experimental data were generated from a set of wave tank model tests and the results were scaled up using a scale factor of 1:55. The thickness of marine growth applied on the model pipe was varied with respect to the water depth in the ratio of 3:2:1. Regular waves were generated with wave heights ranging from 0.02 m to 0. 2 m for modal period varying from 0.6 s to 3.25 s. The tests were conducted for Keulegan-Carpenter number ranging from 3.9 to 23.3. The findings of the experimental results revealed that increasing the thickness of the full scale prototype cylinder by 110 mm due to marine growth fittings, has increased the overall wave hydrodynamic forces by 16 to 90% depending on the wave heights and the wave frequencies at which the model was tested, proving that the drag coefficients have considerably increased.

Introduction

Marine growth is commonly defined as unwanted surface coat caused by marine organisms such as plants, animals, micro-organisms, bacteria and algae, on underwater surfaces of marine structures, ships, buoys, offshore platforms, etc.[1]. From the structural view point, knowledge on the effects of marine fouling on offshore structures is important for accurate estimation of hydrodynamic loading on these structures [2] as marine growth can increase the tubular pipe diameters and consequently, the added mass and the hydrodynamic loading increase. This phenomenon can result in hydrodynamic instability, as a result of vortex shedding and possible corrosion effects [1]. According to the existing literature, marine growth varies based on the geographical location, as well as with respect to water depth. For instance, in Malaysian offshore locations, marine growth thickness of up to 127 mm is to be considered in wave force computations, with dry unit weight of marine growth to be taken as 10 kN/m^3 [3] Designers normally use Morison equation to estimate the hydrodynamic forces on rough and smooth slender tubular members. To accommodate the effects of surface roughness during the estimation of hydrodynamic forces, the codes of practice specify modified coefficients. For tubular smooth cylinders Cm = 1.60 and Cd = 0.65, while the specified values for inertia and drag coefficient for rough tubular cylinders are 1.2 and 1.05 respectively [3], [4]. However, drag and inertia coefficients are not constant; they are functions of Keulegan-Carpenter number and Reynolds number [5]. Hence, several successful research studies have been conducted to determine the hydrodynamic coefficients of tubular cylinders experimentally. For instance, the pioneering study was conducted by Morison et al.[6]. Much later, extensive laboratory research was conducted by Sarpkaya [7]. In this study, the author correlated the hydrodynamic coefficients of smooth cylinder with Reynolds number and Keulegan-Carpenter number. In addition, Chakrabarti [8] conducted another study in the wave to determine the hydrodynamic coefficients of a vertical cylinder and the results were compared with those presented by Sarpkaya [7]. Additional materials in this topic can be found in [9], [10], [11], [12], [13] and [14]. Further, several research have also been conducted to estimate the effects of marine growths on hydrodynamic coefficients. Detailed study in this topic was presented by [12], [2] and [15]. However, to the author's knowledge, literature that addresses the effects of marine growth on hydrodynamic coefficients for Malaysian waters are not available. The Malaysia offshore locations are generally situated in the monsoon regime.

Theoretical Formulations

Calculation of Hydrodynamic Forces. In offshore engineering, the determination of accurate wave forces exerted on structures is very complex and cumbersome task. Morison equation is generally used for estimating the external viscous hydrodynamic forces on tubular cylinders subjected to wave loadings [6]. Morison equation assumes that the total in-line hydrodynamic force on a tubular cylinder consists of inertia and drag forces added linearly. The total hydrodynamic forces over the full water depth due to drag and inertia can be estimated using Equation 1.

$$F=\int_0^d f ds=\int_0^d [C_m \frac{\rho\pi D^2}{4}\frac{du}{dt} + C_d \frac{\rho D}{2}\left|u+U_c\right|(u+U_c)\,]ds \tag{1}$$

where d is the water depth, D is the pipe diameter, u is the horizontal water particle's velocity, U_c is the current velocity, du/dt is the water particle's acceleration, C_m and C_d are the hydrodynamic inertia and drag coefficients respectively and ρ is the water density, and ds indicates the length of integration which is done over the wetted length of the cylinder. The linear airy wave theory, which is applicable when the amplitude is small compared to the wave length and the water depth, gives the horizontal water particles velocity and accelerations as:

$$U_{ix}=\frac{\partial\Phi_i}{\partial x}=\frac{\pi H\cosh ks}{T\sinh kd}\cos\theta \tag{2}$$

and

$$\dot{U}_{ix}=\frac{\partial U_{ix}}{\partial t}=\frac{2\pi^2 H\cosh ks}{T^2\sinh kd}\sin\theta \tag{3}$$

Determination of Hydrodynamic Coefficients. The values of drag and inertia coefficients can be determined by substituting the measured hydrodynamic forces in Equation 1, and estimating the wave kinematics using airy waves theory,. As the values of *Cm* and *Cd* are functions of the phase angle θ , the best combination of *Cm* and *Cd* and the corresponding phase angles that satisfy Equation 1 have been selected as the optimum drag and inertia coefficients for each loading case.

Experimental Details

Wave Tank Details. The model experiments were carried out in the wave basin of Universiti Teknologi PETRONAS (UTP). The wave tank dimensions are 20 m by 10 m with a maximum water depth of 1 m. Regular waves were generated with wave heights ranging from 0.02 m to 0.2 m, for modal periods varying from 0.6 s to 3.25 s. The wave-maker was controlled through an integrated remote control software package capable of generating regular, irregular and multidirectional waves, while the wave profiles were recorded using four wave probes placed around the model. Two wave probes were placed before the model, whilst the remaining two were placed after the model at a center to center spacing of 1.8 m.

Experimental Set up and Procedures. As depicted in Fig. 1, two vertical rigid cylinders were subjected to regular waves. The first cylinder was smooth, while the second was covered with marine growth. The two models were vertically mounted on the overhead bridge to form a rigid connection at one end, while the other end of each cylinder was immersed in the wave tank to form a cantilevered beam. The model pipes were made of galvanized steel. The outer diameter of the smooth pipe was D_{os}= 42 mm and its wall thickness t_1= 2.5 mm, while the second model with marine growth has an average outer diameter D_{or}= 45 mm. The wave forces were measured using wave force sensors designed and fabricated by the research group in UTP. Details of the wave load sensor used in this study was published earlier by Idichandy [16]. The physical properties of the model and the scaled up full scale prototype details are shown in Table 1 and 2.

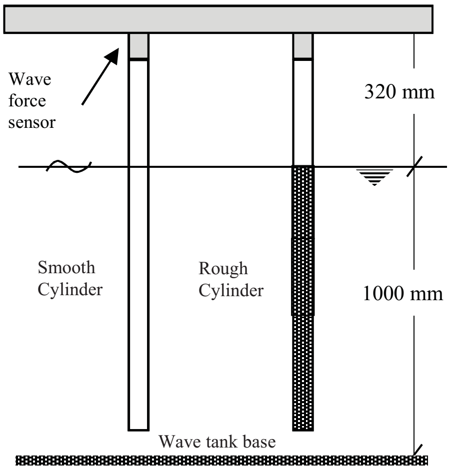

Figure 1. : Fixing details of the model in the wave tank

Table 1: Properties of the model and the prototype

Model			Prototype		
Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (m)	Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (m)
0.042	1.23	0.0032	2.31	68.75	0.176

Table 2: Details of marine growths with respect to water depth [3]

Model			Prototype		
Water Depth (m)	Pipe Outer Diameter (mm)	Marine Growth Thickness (mm)	Water Depth (m)	Pipe Outer Diameter (mm)	Marine Growth Thickness (mm)
MSL - 0.2	47	2.5	MSL - 12	2585	137.5
-0.2 - 0.40	46	2	12 - 21	2530	110
-0.40 - Seabed	45	1.5	-21- Seabed	2475	82.5

Wave Tank Loading Conditions. Table 3 depicts the different wave periods and the associated wave frequencies generated in the wave tank during the model test. These wave periods were generated using modal wave heights of 0.2 m, 0.15 m and 0.1 m as shown in Table 4. The corresponding prototype wave heights are 11 m, 8.25 m and 5.5 m respectively. The hydrodynamic forces and the associated hydrodynamic coefficients for the prototype resulting from these loading conditions were scaled up using a scale factor of 1:55 and the findings are discussed in the following sections. The Reynolds number and Kuleugan-Carpenter number for the prototype can estimated using the scaled up parameters in accordance with the well-known similitude theory.

Table 3: Details of wave characteristics generated in the wave tank

Model	Prototye		
Wave Periods (*s*)	Frequency (*Hz*)	Wave Period (*s*)	Frequeny (*Hz*)
1	1	7.416	0.135
1.5	0.667	11.124	0.090
2	0.500	14.83	0.067
2.5	0.400	18.540	0.054
3	0.333	22.249	0.045

Table 4: Details of wave heights generated in the wave tank

Model	Prototype
Wave Height (m)	Wave Height (m)
0.2	11
0.15	8.25
0.1	5.5

Results and Discussions

Hydrodynamic Forces. Fig. 2 shows the hydrodynamic forces for a smooth rigid cylinder with outer diameter of 2.31 m, compared with the responses of a similar cylinder with the same physical properties, fitted with marine growth to increase its surface roughness which can be defined as a measure of the texture of a given surface. The surface roughness was achieved using sand paper type SDP34. The results show that, when the smooth pipe was subjected to regular wave with H_{max} = 11 m, and wave period T = 11.13 s, the hydrodynamic force was 690.6 kN. However, when marine growth was applied to the same pipe and the test was repeated with the same loading condition, the results show that the average hydrodynamic force on the cylinder was 803.6 kN, an increase of 16 % on the total hydrodynamic force. This clearly shows the effects of marine growths on the hydrodynamic forces of tubular cylinders. In addition, while keeping the wave height constant at 11 m, due to space limitations, the wave period was increased from T = 11.13 s to 14.8 s and the forces were measured. As shown in Fig. 3, the average hydrodynamic force on the smooth cylinder was 473.6 kN, whilst the corresponding response of the rough cylinder was 780.8 kN, an overall increase of 65% on the hydrodynamic forces due to marine growths effects. Moreover, it can also be observed that although in both the above cases, the marine growth thickness was the same, changing the wave period has considerably influenced the hydrodynamic responses of the prototype. The average force is estimated by taking the average of the force height from the graphs.

Similarly, the wave period was increased from 14.83 s to 18.54 s, then to 22.24 s and the hydrodynamic forces were investigated. As shown in Fig. 4, the marine growth fittings have increased the responses of the full scale prototype from 262.2 kN to 505.5 kN, an increase of 90%. However, when the wave period was increased to 22.24 s, the response of the pipe fitted with marine growth has comparatively produced smaller hydrodynamic forces as depicted in Fig 5. The hydrodynamic force decreased by 20% i.e. from 682.1 kN to 542.8 kN. The reason can be associated with the wave frequency generated for this particular loading case; however, in-depth further investigations need to be conducted to prove this experimentally.

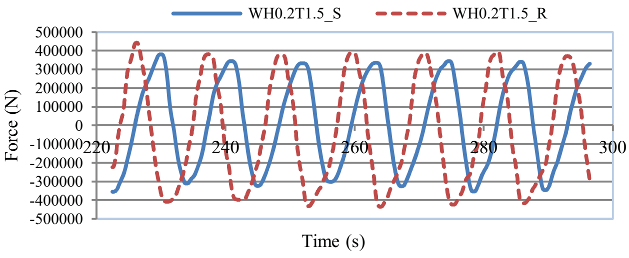

Figure 2: Hydrodynamic forces for 2.31 m diameter, rough (R) and smooth (S) cylinders subjected to regular waves with H_{max} = 11 m and T = 11.12 s

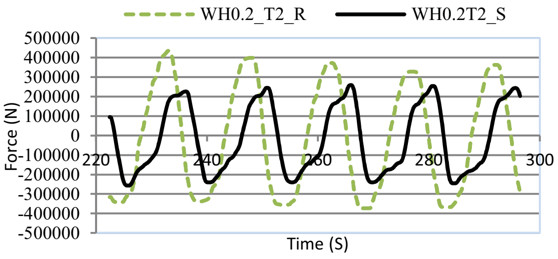

Figure 3: Hydrodynamic forces for 2.31 m diameter, rough (R) and smooth (S) cylinders subjected to regular waves with H_{max} = 11 m and T = 14.83 s

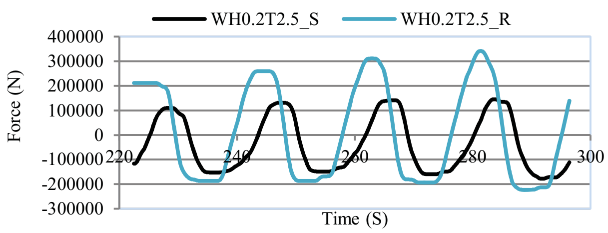

Figure 4: Hydrodynamic forces for 2.31m diameter, rough (R) and smooth (S) cylinders subjected to regular waves with H_{max} = 11 m and T = 18.54 s

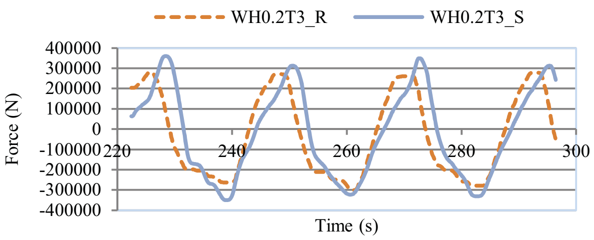

Figure 5: Hydrodynamic forces for 2.31m diameter, rough (R) and smooth (S) cylinders subjected to regular waves with H_{max} = 11 m and T = 22.25 s

Estimation of Hydrodynamic Coefficients. In this section, drag and inertia coefficients for smooth and rough tubular cylinders, subjected to regular waves are discussed. The hydrodynamic forces were determined using the well-known Morison equation and *Cm* and *Cd* were determined by equating the measured forces to the theoretical values estimated using the wave kinematics. The hydrodynamic coefficients are determined for different loading conditions as discussed in the following paragraphs.

Fig. 6 shows the scaled up drag and inertia coefficients for the full scale prototype cylinder with outer diameter D_o = 2.31 m subjected to regular waves with H_{max} =11 m, and wave periods varying from T =11.12 s to 24.1 s. The results show that the minimum drag coefficient, *Cd* = 0.4, while the maximum *Cd* = 1.14 recorded at T = 18.50 s and T = 22.25 s respectively. The corresponding minimum and maximum *Cd* values for the rough cylinder are 1.05 and 1.77 recorded at T = 22.25 s and 14.83 s respectively. In addition, the inertia coefficients for the smooth cylinder varied from *Cm* = 1.03 to 2.8. Similarly, the inertia coefficient *Cm* for the cylinder with marine growth fittings varied from *Cm* =1.3 to 2.03, with the minimum and maximum values observed at T = 22.25 s and T = 14.83 s respectively. Further, as depicted in Fig. 7, the prototype was subjected to regular waves with H_{max}= 8.25 m and the corresponding hydrodynamic coefficients were determined. The values of *Cd* corresponding to rough cylinder were higher than that of smooth pipe. The *Cm* values also showed slight increment due to marine growth fittings. Generally, the analysis of the results show that some of drag and inertia coefficients determined experimentally in this study are in good agreement with the limits of *Cm=1.60* and *Cd* =0.65 specified in PTS [3] and API [4], while the large part of the findings are comparatively smaller than the specified values, which is encouraging for design of more economical offshore platforms for Malaysian waters.

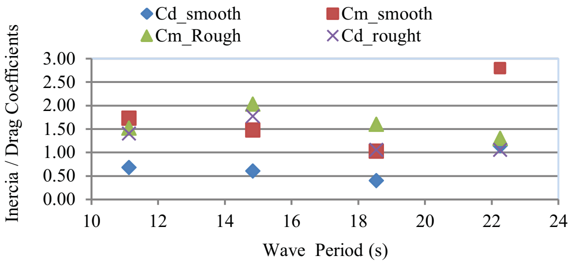

Figure 6: Hydrodynamic coefficients for 2.31 m diameter, rough and smooth cylinders subjected to regular waves with H_{max} = 11 m

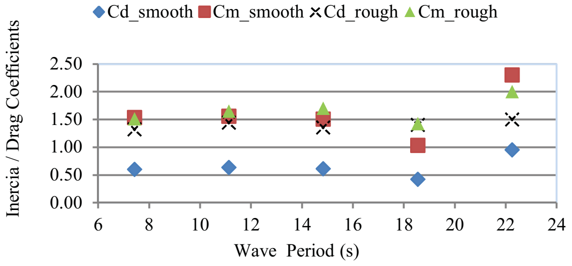

Figure 7: Hydrodynamic coefficients for 2.31 m diameter, rough and smooth cylinders subjected to regular waves with H_{max} = 8.25 m

Concluding Remarks

From the model tests on the effects of marine growths on drag and inertia coefficients, the flowing conclusions can be drawn for the prototype:

1. Applying average marine growth thickness of 110 mm to a tubular cylinder with outer diameter of 2.31 m has increased its hydrodynamic forces by 16 to 90% depending on the wave heights and the wave frequencies of the loading condition.

2. Generally, increasing the surface roughness of the tubular cylinder has increased the drag coefficients significantly. The effects of marine growth fittings on inertia coefficients were generally small as compared to drag coefficients.

3. Drag and inertia coefficients determined experimentally in this study are in good agreement with *Cm* and *Cd* values specified by the design code of practices. The large part of the findings are comparatively smaller than the specified values, which is encouraging for design of more economical offshore platforms for Malaysian offshore locations.

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