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Model Tests for Dynamic Responses of Float-over Barge in Shallow Wave Basin

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ABSTRACT

This paper discusses the model test results of float-over barge used for the installation of topsides onto jacket platform, which were carried out in the shallow wave basin of Universiti Teknologi PETRONAS. The objective of the paper is to highlight the importance of determining the single barge responses prior to performing multi-body dynamic analysis of float-over installations. As part of developing the industrial capability of model testing in this wave basin as an indispensable component of the design of float-over barge, the methodologies and procedures for test setup, execution and analysis are described in this paper. Furthermore, the method of data analysis using advanced numerical method for regular wave named Filon Quadrature method are discussed and the test results are presented in terms of first order responses, namely RAOs of the barge for head and beam seas. Results of the model tests were cross-checked with the results of established diffraction method using 'WAMIT' and were found to be generally in good agreement for predicting the dynamic responses of float-over barge subjected to waves.

KEY WORDS: Float-over barge; first order responses; model tests; diffraction method.

INTRODUCTION

The float-over method is known as a flexible alternative to lifting method due to several distinct advantages. From the installation point of view, this method is not restricted by the availability of heavy lift crane vessels. These vessels are difficult to mobilize in remote areas and the cost associated with the mobilization and de-mobilization of such vessels is prohibitively expensive. This drawback has led the operators and contractors to consider the float-over method which is more feasible for diverse range of offshore locations.

Other advantages include the reduction in the overall cost of platform construction as the topsides can be fully fabricated, outfitted and commissioned onshore prior to load out. As opposed to the conventional lifting installation using derrick barges, the increase in the deck weight has necessitated multiple lifts to be used when the crane lifting capacity is exceeded. As a result, significant amount of hook-up and commissioning work needs to be done. Float-over method allows the hook-up and commissioning to be minimized resulting in substantial cost savings.

This concept is considered suitable for heavy topsides, exceeding the capacity of available heavy lift barges. The deck installation using this method reduces cycle time and offers schedule benefits due to less offshore hook-up and commissioning. It is estimated that offshore welding, pipe-fitting, instrumentation and electrical connections between modules and subsequent commissioning will cost 3-8 times more than the equivalent operations at the fabrication yard and involve significantly increased risk to personnel.

One of the technical challenges associated with float-over installation is the estimation of barge motions during the operations. The responses of the barge are important as the barge motions have to be limited during float-over installation to prevent excessive contact between barge, deck and jacket leg. In this respect, the dynamic responses of moored float-over barge are very critical and must be evaluated to ensure successful float-over operations. The design sequences of float-over installation need important data such as design wave environment for the operations as well as the estimation of barge responses at installation site during standby phase and when the barge is ballasted and moored. Determination of these dynamic responses is the subject of investigation of the present study. In addition, the parameters such as barge draft/ballast conditions and wave headings are important for motion and stability assessment. This has been investigated by means of model tests and diffraction method where two drafts were selected to represent different stages of float-over installation.

Estimation of Dynamic Responses of Float-over Barge

The dynamic responses of the float-over barge could be estimated based on numerical simulation, model tests, field installation data and analytical solutions. Koo *et al.* (2010) investigated the feasibility of topside installation onto a spar by float-over method for operational sea states in the Gulf of Mexico. The physical modeling studies were conducted at a scale of 1:60 to generate the data on the motions and loads during different phases of float-over operations such as transportation, mating and barge withdrawal. Three different headings were considered in their study (head, beam and quartering seas) to demonstrate the range of wave directionalities associated with float-over installations.

Tahar *et al.* (2006) studied on the float-over deck installation concept developed by Technip Offshore Inc. using semi-submersible barge type vessels. The comparisons between model test data and numerical predictions were made for the installation of integrated deck having weight of 28,000 t onto a compliant tower in West Africa. A numerical simulation was conducted in time domain using MLTSIM to analyze the dynamic response of a multi-body floating platform subjected to wind, wave and current. The first-order diffraction program, WAMIT was used to calculate the added mass, hydrodynamic damping and first-order wave frequency forces for the barge. In this analysis, the hydrodynamic interaction between the compliant tower and the barges were neglected. They proposed that the float-over operations based on this concept are more suitable for swell conditions as heave forces due to waves are reduced allowing smooth load transfer process. Overall results reflected satisfactory agreement between numerical analysis and model test.

Chu *et al*. (1996) investigated the float-over installation of integrated deck onto the pre-installed concrete gravity substructure in Wandoo field, North Australia using computer simulation, model test and field installation data. The authors conducted numerical study in order to determine the hydrodynamic force RAO's, added mass and damping of the floating barge. The hydrodynamic forces on the barge were calculated using wave diffraction theory and the analyses were performed at varying drafts simulating the different phases of float-over installation.

Dixen (2009) reported model test studies to simulate the installation of Gravity Based Structure (GBS) using an installation barge. The motion responses of the coupled system were determined during different stages of installation. The wave tank tests were carried out for six different sea states and the measurements were made for six degrees of freedom motions of the coupled system, consisting of a barge and GBS. The motions of the barge model were secured with four mooring lines located at four corners of the barge.

Xia et al. (2005) conducted model tests for float-over installations to investigate motions of a barge and the loads exerted on jacket. In their paper, the response amplitude operators of the barge motions were determined for free floating conditions.

For the study presented in this paper, the model tests on float-over barge were conducted in the free floating condition. The responses of the barge were determined during standby phase of the float-over installation where the barge is at safe distance from substructure but connected to the mooring system. The main objective of this study was to determine the dynamic responses of float-over barge subjected to random waves by scale model testing and to compare with the numerical results based on diffraction method using WAMIT.

METHODOLOGY

Model Tests of Float-over Barge

Model Testing Facilities

The scaled model tests of float-over barge were carried out in the wave basin of the Offshore Engineering Laboratory located at Universiti Teknologi PETRONAS (UTP). The model testing facility reported in this study consists of 10 m wide, 22 m long and 1.2 m deep wave basin. As float-over operations typically take place in water depth less than 70 m, the UTP wave basin is ideal for carrying out such tests. The wave basin is equipped with multiple paddle wave makers capable of generating regular and random waves. Along the side opposite to the wave maker there is a dynamic wave absorber to minimize the reflection from the waves and tank instrumentation such as wave probes. Other instrumentations are the load cells, the accelerometers, and the optical tracking system to measure the tensions in the mooring lines, accelerations and motions of the barge model respectively. The wave basin is also equipped with two movable remote control bridge platforms to support the testing personnel and equipment. Fig. 1 shows the view of UTP shallow wave basin.

Fig.1 UTP Wave Basin

Modeling Laws

The most common dimensionless scaling law for the fluid-structure test is the Froude's Law. Froude's Law is used extensively than any other hydrodynamic scaling laws in the physical modeling study (Chakrabarti 1994, 2002). Knowing that the dynamic motion of the structure is governed by the gravitational effect and inertia forces, the Froude Scaling Law was employed for relating the model to prototype. The scale of 1:50 was chosen considering the important factors such as water depth, wave generating capability and accuracy of measurements. The barge model was constructed using marine plywood with non-water tight bulkheads to divide the model into separate chambers representing the prototype's ballast tank. Also, the model consisted of seven ballasts tanks with removable hatch covers for the purpose of providing solid or water ballasts to the model. Fig. 2 shows the fabricated barge model. The particulars of the float-over barge both in full scale and model scale are given in Table 1.

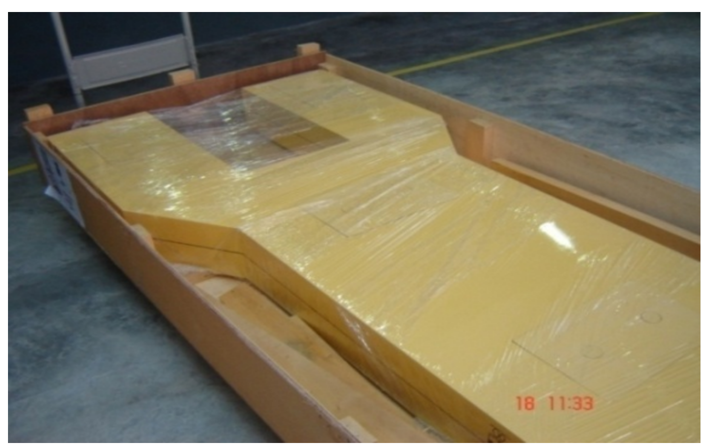

Fig.2 Fabricated barge model

Table 1. Float-over barge parameters both in full scale and model scale

Description	Full Scale Values	Model Scale Values
Length	159.76 m	3.2 m
Width at bow	30 m	0.6 m
Width at stern	45.72 m	0.91 m
Height	8 m	0.16 m
Lightship weight	7575 MT	60 kg
Centre of gravity, X_g	80.95 m	1.619 m
Centre of gravity, Z_g	4.05 m	0.081 m
Radius of gyration, r_x	8.96 m	0.18 m
Radius of gyration, r_y	46.18 m	0.92 m
Radius of gyration, r_z	46.92 m	0.94 m

Model Test Setup and Test Condition

The forked barge concept was designed for the installation of topsides in Caspian Sea with relatively benign environment. The arrangement at the stern of the barge was designed to transport and install topsides onto jacket type of platform. Model tests of the float-over barge were conducted in the wave basin to determine the motion responses of the barge using 1:50 scale model of a float-over barge. This test takes into account the responses of the float-over barge in terms of motions in six degrees of freedom and the motion measurements were made relative to centre of gravity of the barge model. The displacements of the barge model were recorded by an optical tracking system that used four cameras and reflective markers. Five reflective markers each with different height were placed on the deck of the barge model to measure surge, heave, sway, roll, pitch and yaw motions. The measured responses were scaled up to obtain the values of prototype data. Measurements were also made for the loads in the mooring lines. The barge model was restrained by four symmetrical mooring systems comprising of wires attached to linear spring with a stiffness of 28.54 N/m each anchored to the posts of specially fabricated ring. The tensions in the mooring lines were measured by load cells placed at the fixed end of the fabricated posts. Before the test commenced, the mooring lines were adjusted to achieve pretension of 30 N. Figs. 3 and 4 show the schematics of the model test setup and Figs. 5 and 6 show the barge model as installed in the wave basin.

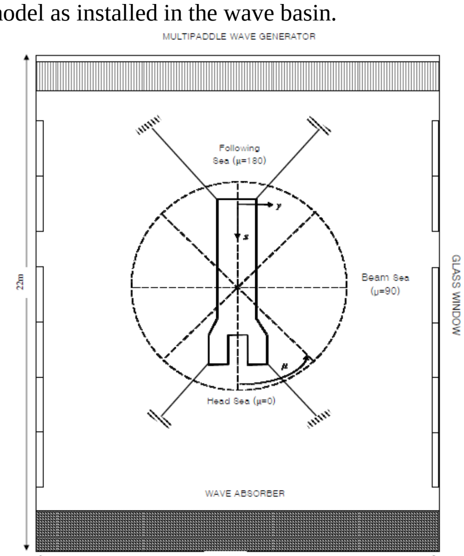

Fig.3 Schematics of Model Test Setup

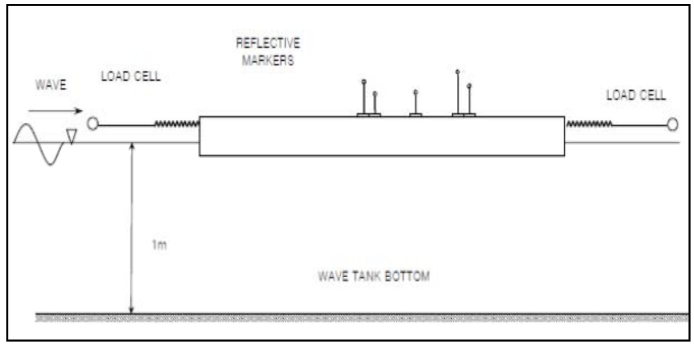

Fig.4 Model Test Setup for Motion Measurement

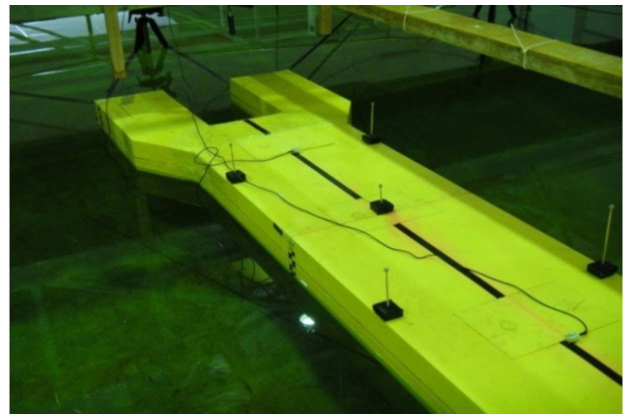

Fig.5 Barge model as installed in wave basin

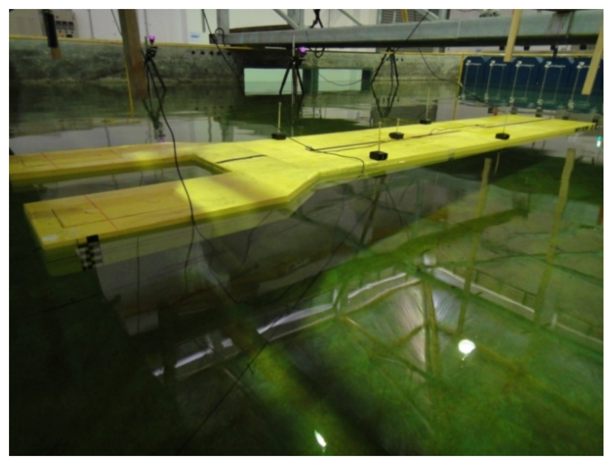

Fig.6 Float-over barge model test in regular waves

Data Analysis

Regular Wave Analysis

The design wave environment for floating offshore platforms consists of two basic approaches. One of these uses a regular wave method or single wave method represented by a wave period and wave height. In this study, the regular wave data were analyzed using Filon quadrature method that was used to evaluate highly oscillating integrals of regular wave signals obtained from the model tests (Fosdick 1967, Tuck, 1996). Initially, the regular wave results were analyzed using filtering function available in MATLAB but due to some limitation, the use of an advanced numerical method named Filon-Simpson method was resorted to extract the transfer functions from regular wave results. The analysis involved the truncation of calibrated wave and motion time series and the use of Filon Simpson method to determine the response transfer function. In order to evaluate the Fourier integrals of regular wave signals, a MATLAB code was written for Filon-Simpson quadrature method. The Filon quadrature formulas can be found in Appendix. The outcomes were the amplitudes and phase angles of the wave and motion time series. The transfer functions in terms of Response Amplitude Operators (RAO) are defined by Eq. 1

$$RAO = \frac{\zeta_n e^{i\varphi n}}{\eta_5 e^{i\alpha 5}} \tag{1}$$

where ζ_n is the amplitude of motion in six degrees of freedom, φ_n is the phase angle of motion in six degrees of freedom, η_5 is the wave amplitude at the reproduction point during waves calibration and α_5 is the phase angle of the calibrated wave time series at the reproduction point. The transfer functions of regular wave results were determined based on incident wave at the wave reproduction point. This harmonic analysis was found useful and accurate in evaluating the transfer functions for regular wave data and can be used to check the random wave results. Since the floating platforms exhibit low frequency responses, the low frequency responses can also be separated and assessed from the model tests. Furthermore, this program can be used to develop industrial capability for model tests and used for the future experiments conducted in the wave basin.

Random Wave Analysis

Data post-processing program was used to convert the measured responses to response spectra using Discrete Fast Fourier Transform (DFFT). The Response Amplitude Operators (RAOs) were obtained from the response spectra by assuming a linearly dampened dynamic system. The experimental RAO (or transfer functions) for random wave were determined from Eq. 2

$$RAO = \sqrt{\frac{S_R(f)}{S(f)}} \tag{2}$$

where S_R is the response spectra in six degrees of freedom, S is the wave spectrum and f is the cyclic wave frequency.

Diffraction method

A second order diffraction-radiation method, WAMIT was applied to perform hydrodynamic calculations of the float-over barge. The program is widely recognized in the oil and gas industry for its analysis capability. Table 2 gives the input for diffraction analysis using WAMIT.

Table 2. Input for diffraction method using WAMIT

Parameter	Unit	Draft (4 m)	Draft (6.75 m)
Water depth	m	50	
Fork length	m	29.76	
Fork width	m	15	
Fork gap	m	15.72	
Transit-part length	m	12.0	
Draft	m	4	6.75
Displacement	t	20029.4	33799.6
KG (from keel)	m	9.3	8.6
Radii of gyration - Roll	m	9.3	8.6
Radii of gyration - Pitch	m	45.9	41.9
Radii of gyration - Yaw	m	46.8	42.7

RESULTS AND DISCUSSION

Figs. 7 to 18 summarize the results of barge responses in head and beam seas for 4 m and 6.75 m drafts. The barge model was tested under regular wave sea state with wave height of 1.86 m and wave period of 6 s to 10 s and random wave sea state with significant wave height 2 m and peak wave period of 7 s at water depth of 1 m in the wave basin. The surge, heave and pitch transfer function were plotted for head seas and the sway, heave and roll transfer functions were plotted for beam seas to compare idealized responses in regular waves with the frequency dependent responses in realistic random wave and the results from diffraction method using WAMIT. Since reliable transfer functions can only be obtained where there is sufficient wave energy, the transfer functions derived from the model tests were plotted from 0.08 Hz to 0.4 Hz.

Comparison between model tests and diffraction method using WAMIT for head seas

Transfer Functions for 4 m draft

The surge transfer function obtained from model tests and diffraction method show similar trends for almost entire range of frequencies with slight differences at frequency range of 0.16 to 0.2 Hz. The result for surge transfer function is shown in Fig. 7. Comparison with the results of model test and diffraction method shown in Fig. 8 produced satisfactory results with heave RAO showing higher responses at certain frequencies. At frequency of 0.11 Hz (T= 9 s), heave RAO have percentage difference of 32% when compared to diffraction response. For pitch response, the comparison shows difference at frequency of 0.125 Hz with percentage difference of 21% as shown in Fig. 9. However, the trend and magnitudes are in reasonable agreement between regular wave, random wave and diffraction method. The maximum pitch RAOs predicted by model tests and diffraction method are 0.46 deg/m and 0.61 deg/m respectively.

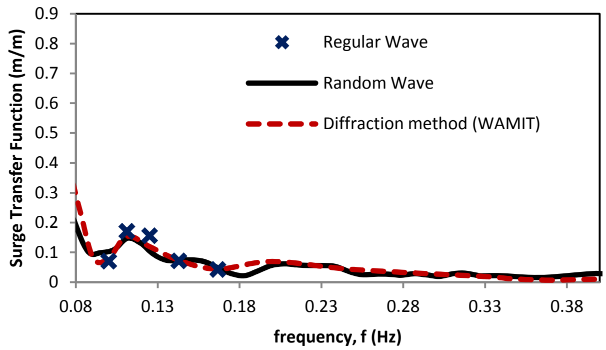

Fig.7 Surge transfer function for 4 m draft (head seas)

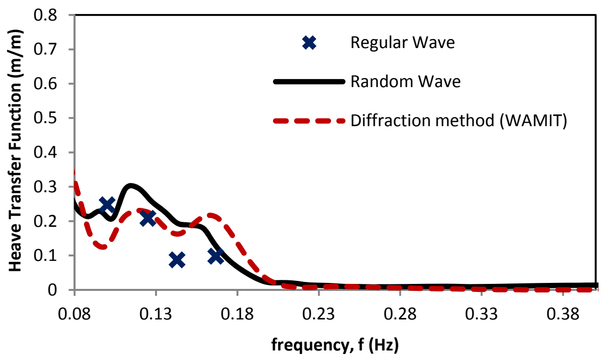

Fig.8 Heave transfer function for 4 m draft (head seas)

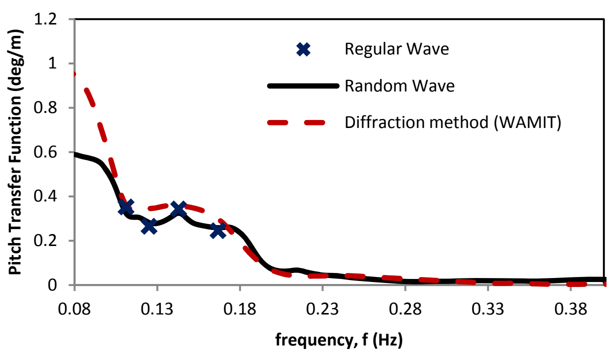

Fig.9 Pitch transfer function for 4 m draft (head seas)

Transfer Functions for 6.75 m draft

The results for surge transfer function for 6.75 m draft are shown in Fig. 10. The surge RAO shows lower response for almost entire range of frequencies except at low frequency of 0.08 Hz. This was probably due to wave force cancellation due to equal and opposite forces induced by wave action. At wave period of 7 s, the ratio of the wave length to the length of the barge, λ/L is 0.48, that is close to half of the length of the barge. The wave cancellation probably occurred thus affecting the surge response transfer function.

Comparison between model tests and diffraction method shown in Fig. 11 produced satisfactory results with heave RAO showing good agreement. For pitch response, the comparison shows agreement in terms of trend but with lower magnitudes than the diffraction response as shown in Fig. 12. The pitch RAO extracted from regular wave analysis using Filon-Simpson method are in better agreement with diffraction response than random wave response.

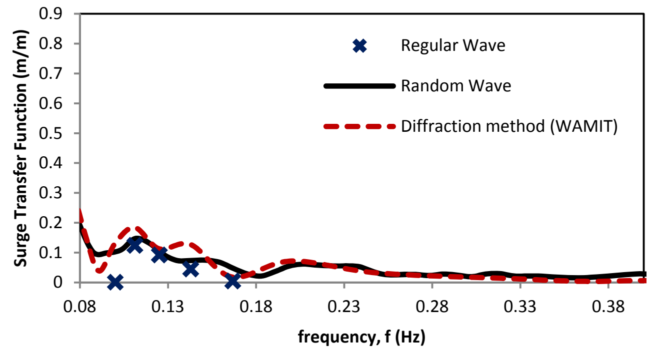

Fig.10 Surge transfer function for 6.75 m draft (head seas)

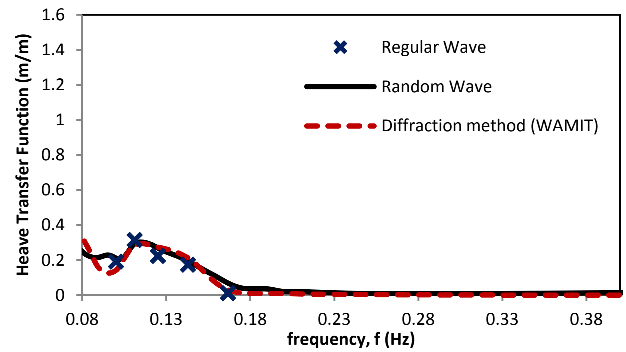

Fig.11 Heave transfer function for 6.75 m draft (head seas)

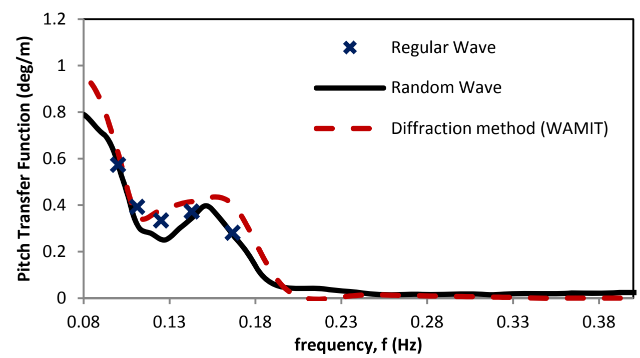

Fig.12 Pitch transfer function for 6.75 m draft (head seas)

Comparison between model tests and diffraction method using WAMIT for beam seas

Transfer Functions for 4 m draft

For the sway RAO comparison, diffraction results are in good agreement with the model test responses for both regular and random wave, in both magnitude and trend for almost entire range of frequencies as seen in Fig. 13. The heave RAO comparison is shown in Fig. 14. Heave RAO obtained from model tests shows a similar pattern to the diffraction method but with lower magnitudes than the latter. A marked difference can be seen at frequency of 0.125 Hz between measured and calculated response. The regular heave RAO agreed with diffraction method except at frequencies of 0.125 Hz and 0.111 Hz corresponds to wave period equals to 8 s and 9 s respectively. At these two frequencies, regular waves RAOs are in good agreement with the measured random wave response.

Fig. 15 shows roll responses obtained by hydrodynamic model tests and diffraction method. For random wave, the measured roll response is smaller than that calculated by diffraction method indicating that the roll motion was damped out by viscous effects during model tests while for regular wave, the measured roll responses show good agreement with numerical responses at 7 s and 10 s wave periods. The difference in peak values of measured roll RAO with roll responses calculated by diffraction method is about 18% with the magnitude of peak values of former being about 84% of the latter. These discrepancies are probably due to viscous-damping effects that were not accounted in diffraction analysis.

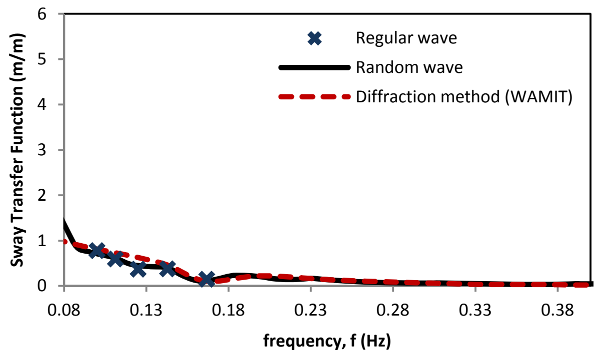

Fig.13 Sway transfer function for 4 m draft (beam seas)

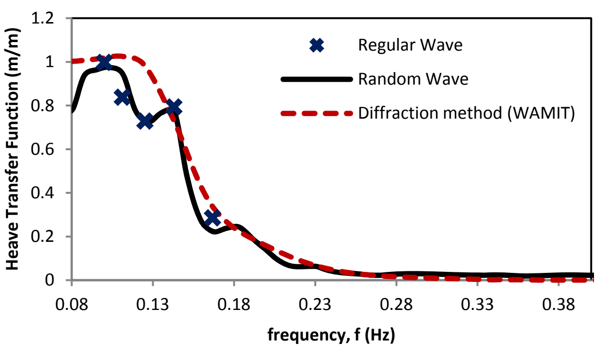

Fig.14 Heave transfer function for 4 m draft (beam seas)

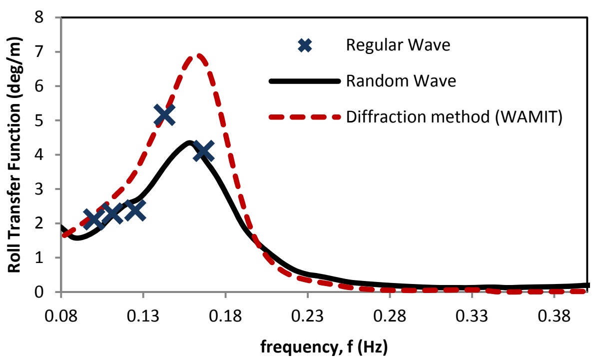

Fig.15 Roll transfer function for 4 m draft (beam seas)

Transfer Functions for 6.75 m draft

Figs. 16 to 18 show the motion RAO between model tests both in regular and random wave sea states and diffraction method. The agreement is satisfactory in the case of sway responses except at wave period of 6 s, where the diffraction response is two times of the random and regular wave RAO, as shown in Fig. 16. The comparison for heave RAO is presented in Fig. 17. For heave response, the results compared well between random wave and the calculated response. Regular wave RAO confirmed the validation by showing good agreement for all frequencies except at frequency of 0.142 Hz with calculated heave response. The comparison between random, regular and diffraction for roll response are shown in Fig. 18. In this case, the calculated roll response is greater than both measured data. The calculated roll response by diffraction method shows difference of about 8% at the peak values.

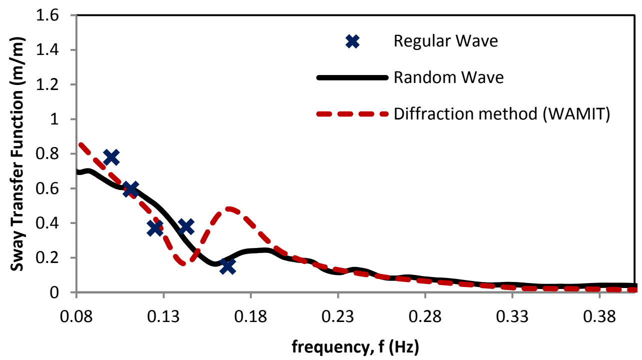

Fig.16 Sway transfer function for 6.75 m draft (beam seas)

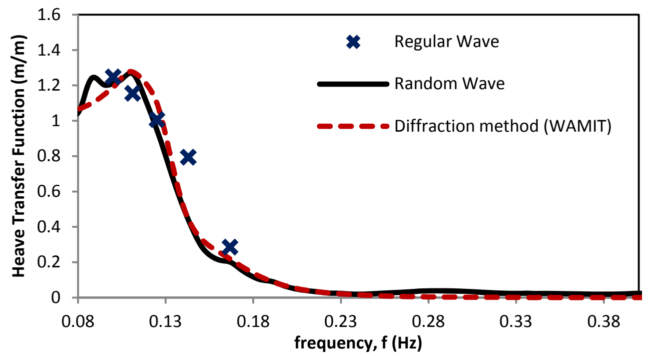

Fig.17 Heave transfer function for 6.75 m draft (beam seas)

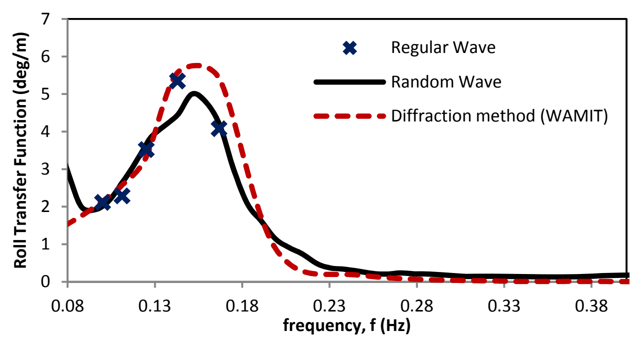

Fig.18 Roll transfer function for 6.75 m draft (beam seas)

CONCLUSIONS

The dynamic responses of float-over barge in head and beam seas were obtained from the model tests conducted in the shallow wave basin of UTP. The wave basin is ideal for float-over operations which typically take place in water depths of less than 70 m. The responses in regular and random waves were then compared with the results from established diffraction-radiation method. The model test results are generally in good agreement with the results of the established diffraction analysis in almost all the cases discussed except for roll responses. Hence it can be concluded that the model tests in this wave basin can be very well made use for prediction of dynamic response of float-over barges.

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APPENDIX

The Filon quadrature formula is used for the numerical evaluation of the form

$$S = \int_a^b x^m \sin(kx)dx\,, \qquad C = \int_a^b x^m \cos(kx)dx$$

The Filon quadrature formula is given by Eqs. 2 and 3 as

$$S = h\left[\alpha(f_0 \cos kx_0 - f_{2p} \cos kx_{2p}) + \beta S_{2p} + \gamma S_{2p-1}\right] + E_s$$

$$C = h\left[\alpha(f_{2p} \sin kx_0 - f_0 \cos kx_0) + \beta C_{2p} + \gamma C_{2p-1}\right] + E_c$$

where

$$S_{2p} = \sum_{i=0}^{p} f_{2i} \sin kx_{2i} - \frac{1}{2}\left[f_0 \sin kx_0 + f_{2p} \sin kx_{2p}\right]$$

$$S_{2p-1} = \sum_{i=0}^{p} f_{2i} \sin kx_{2i-1}$$

$$C_{2p} = \sum_{i=0}^{p} f_{2i} \cos kx_{2i} - \frac{1}{2}\left[f_0 \cos kx_0 + f_{2p} \cos kx_{2p}\right]$$

$$C_{2p-1} = \sum_{i=1}^{p} f_{2i-1} \cos kx_{2i-1}$$

$$\alpha = 1/\theta + (\sin 2\theta)/2\theta^2 - (2\sin^2\theta)/\theta^3\,,$$

$$\beta = 2((1+\cos^2\theta)/\theta^2 - (\sin 2\theta)/\theta^3)\,,$$

$$\gamma = 4((\sin\theta)/\theta^3 - (\cos\theta)/\theta^2),$$

$$\theta = kh$$

$$f_i = f(x_i), \qquad x_{i+1} - x_i = h, \qquad x_0 = a, \quad x_{2p} = b$$