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SURGE FORCES OF A FPSO AT LEE SIDE OF SUBMERGED PLATE IN REGULAR WAVES

Agoes Priyanto[1*], Erwandi[2], Samudro[2]

[1]Marine Technology Department,
Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia,
81310 UTM Skudai,
Johor Malaysia

[2]Laboratorium Hidrodinamika Indonesia,
BPP Teknologi, Kompleks Kampus ITS,
Sukolilo Surabaya,
60112 Surabaya, Indonesia

ABSTRACT

A submerged horizontal plate type breakwater is not only to be good energy dissipates of wave breaking on the top of the plate, but also to generate steady flow and to reproduce shorter waves. This paper assessed a submerged plate which is applied to set up for an Oil/Gas Floating Production Storage and Offloading (FPSO) structure. The wave exciting surge forces of the FPSO at the lee side of the submerged plate were examined by using Boundary Element Method based on the potential theory. In order to verify the numerical results, the model experiments have been carried out in Towing Tank of Laboratorium Hidrodinamika Indonesia, BPP Teknologi. By comparing the numerical results with the experimental ones, the results show that the numerical results have similar tendency to the experimental ones, and it is deduced that the submerged plate reduces effectively the wave exciting surge forces at low wave frequencies.

Keywords: *Submerged plate, wave exciting surge forces, potential theory, floating structure*

1.0 INTRODUCTION

When floating structure terminals in deep water are deployed to serve oil offshore production, storage and offloading, the terminals should withstand their position even in bad weather conditions, and have minimum response motions due to waves. Rubble mound breakwaters are widely used around the world for the construction of artificial harbors and for shore protection works. When sufficient quantity and good quality rubble are not available in the vicinity of the proposed

* Corresponding author: E-mail: agoes@fkm.utm.my

harbor site, then concrete caissons can be used. Both structures cannot be applied to protect a huge floating structure, such as terminal or floating airport in deeper waters. For such conditions, special types of breakwaters, which require less concrete per unit length and are capable of transmitting less wave energy, must be developed. Since in deeper waters most of the wave energy is concentrated near the water surface, a structure is required, which can effectively dissipate or reflect this energy. Immersed horizontal plates were found to be good energy dissipaters due to artificial stimulation of wave breaking on the top of the plates [1]. The horizontal barrier breakwater made from plate structure ("submerged horizontal plate") can be applied and expected to improve the performance as a breakwater due to the additive properties of wave breaking and reflection. Hence, this type of breakwater is expected to reduce the energy transmission towards the lee side of the structure where the floating terminal on location.

The performance of submerged horizontal plate breakwater type had been studied and given clear results that the submerged plate could make the steady flow and reproduce smaller waves of the incoming waves [2, 3, 4]. Moreover, Neelamani and Rajendran [5] had reported the hydrodynamic performance of the depth of submergence of the breakwater was varied in order to find out the appropriate depth of immersion at which the wave transmission was minimum, and summarized the results in terms of design curves on submerged plate. These have motivated the authors to investigate the wave transmission, reflection of the submerged plate and wave forces of the terminal at the lee side of the plate. The submerged plate is installed to the floating structure as shown in Figure 1, and expected to reduce the wave forces and hopefully to minimize the terminal motions in waves.

This paper presents a submerged plate which is applied to set up for a floating structure. The submerged plate parameters, such as the plate's depth of immersion and size, are selected based on the design curves. The appropriate depth of immersion and size of this breakwater is required to achieve the intended wave conditions at the lee side. The present study proved on the characteristics of wave transmission (C_t) for a wide range of wave conditions of the selection plate and compares the C_t results with the numerical computer program MEC [6]. One can decide the permissible wave transmission for a particular oil and gas activity at the lee side of the structure after having known the characteristics of incoming waves. For example, the permissible transmitted wave height is decided about 0.4m, if the incoming waves have the period of 8 second and significant wave height of 2.0m.

The study of energy dissipation character is important to understand the efficiency of the plate as a breakwater. A breakwater can be considered to be performing well if the energy dissipation capability is high. It is also necessary to understand the wave climate at the seaside of the plate due to wave reflection from the breakwater, since the safe navigation of approaching supply vessels is a function of this wave climate. Hence, wave histories are also measured at a typical location at the lee side of the breakwater.

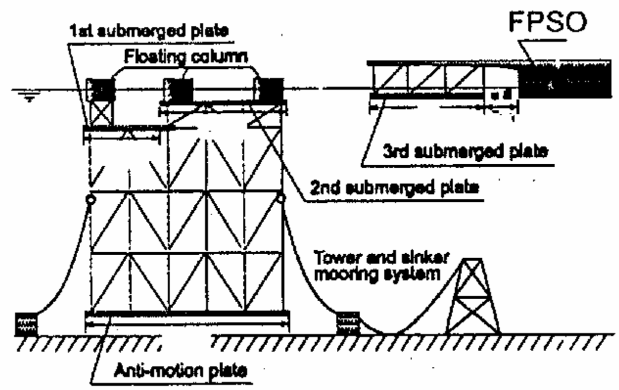

Figure 1: Submerged horizontal plate [4]

Then the hydrodynamic effect of the submerged plate on the wave exciting surge forces are evaluated by boundary element method based on the potential theory. In order to verify the numerical results, the model experiments were carried out in Towing Tank of Laboratorium Hidrodinamika Indonesia, BPP Teknologi.

2.0 EXPERIMENTAL DETAILS

The wave transmission and reflection of the submerged plate, and surge forces of the floating structure at the lee side of the plate were experimentally investigated in a Towing Tank by using physical models. Regular wave is used for the present investigation with the period ranged between 0.8 – 1.24 sec and a constant wave height of 0.04 m. Details of the experimental investigations are given in this section.

2.1 Wave Transmission and Reflection of Plate

Froude scaling is adopted for physical modeling, which allows for the correct reproduction of gravitational and fluid inertial forces. A scale of 1:50 is chosen for the selection of floating structure and submerged plate model dimensions and wave properties in the present study. Table 1 and 2 give details of the proposed prototype conditions and the corresponding model dimensions. The wave transmission and reflection of plate were measured by 3 wave probes (*WP*) on model tests as shown in Figure 2 for a constant water depth of 5.50 m, which corresponds to 275 m water depth in the prototype for 1:50 scale and considers as the deep water. *WP1* measured the incident wave, *WP2* measured reflection wave and *WP3* measured the transmission wave.

Table 1: Wave conditions

Item	Unit	Prototype	Model
Wave period	sec	5,6 – 10.5	0.8 – 1.49
Wave height	m	2	0.04

Table 2: Main particulars of submerged plate

Item	Unit	Prototype	Model
Length	m	30	0.6
Thickness	m	1	0.02
Depth of immersion	m	2	0.04

The reflection estimation gives reflection coefficient (C_r) as the ratio of reflected and incident wave height (i.e. C_r=H_r/H_i). Similarly, the transmission estimation gives transmission coefficient (C_t) as the ratio of transmited and incident wave height. The law of conservation of energy is used for the estimation of the coefficient of energy loss, K_l, since it is not possible to measure it. A breakwater is said to be better if it dissipates most of the incident wave energy. From the law of conservation of energy:

$$C_r^2 + C_t^2 + K_l^2 = 1 \quad (1)$$

$$K_l = \sqrt{1 - C_r^2 - C_t^2} \quad (2)$$

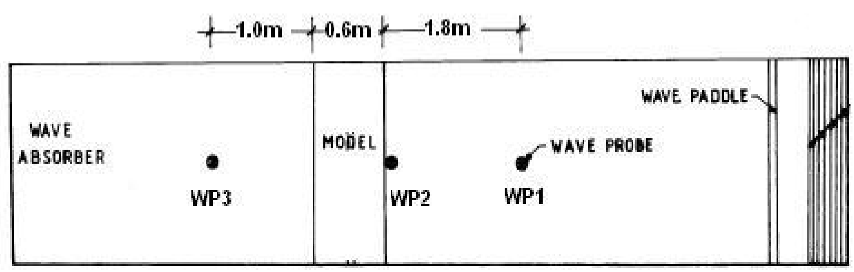

Figure 2: Wave transmission and reflection measurement (*WP1,2,3*)

2.2 Surge Forces on Floating Structure at the Lee Side of Plate

The model is fabricated by using multiplex wood laminated with a fibre sheet. The model consists of two portions, namely a horizontal plate and a floating production storage offloading (FPSO) pontoon. The size of the horizontal plate is $1.95 \times 0.6 \times 0.02$ m^3 and the FPSO pontoon is as shown in Table 3. The plate is fixed rigidly in FPSO pontoon's deck by means of frame steel as shown in Figure 3. The frame steel of $50 \times 50 \times 6$ mm^3 are braced widthwise and lengthwise to ensure strength and rigidity of the plate.

The surge forces at FPSO in wave were measured by a force tranducer fixed at centre of gravity (*CoG*) of the FPSO for two conditions, namely FPSO pontoon only and FPSO with submerged plate. The regular waves were used at model tests, the wave conditions are shown in Table 1.

Table 3: Main particulars of FPSO model

Item	Unit	Prototype	Model
Length (Lpp)	m	285	5.70
Beam	m	58	1.16
Draught	m	6	0.12
Deck's Height	m	27	0.54
Displacement	ton	89,940	0.701
CoG from keel	m	12.6	0.25
CoG from mid	m	0	0

Figure 3: FPSO with submerged plate model

Figure 4: FPSO with submerged plate model in waves

3.0 NUMERICAL COMPUTATION

3.1 MEC Online Computation

The characteristics of wave transmission (C_t) for a wide range of wave conditions of the selection plate were compared with the numerical computer program MEC [6]. The MEC computes the performance of the submerged plate in waves by online. The output results from the MEC online computation is visualized through internet. MEC-Online Computation and Online Visualization can be accessed on the following URL: **http://tsumuji2.ga.eng.osaka-u.ac.jp**

This homepage is also equipped by the user guide and some simply input files as demonstration version on how to use the MEC program. The user guide and generated file input can be downloaded as illustrated in Figure 5. MEC-Online Computation and Online Visualization consists of three application software:

1. MAST web application server
2. MEC main program (MEC-C) and MEC post-processing program
3. AVS Express version 6 to visualize the results

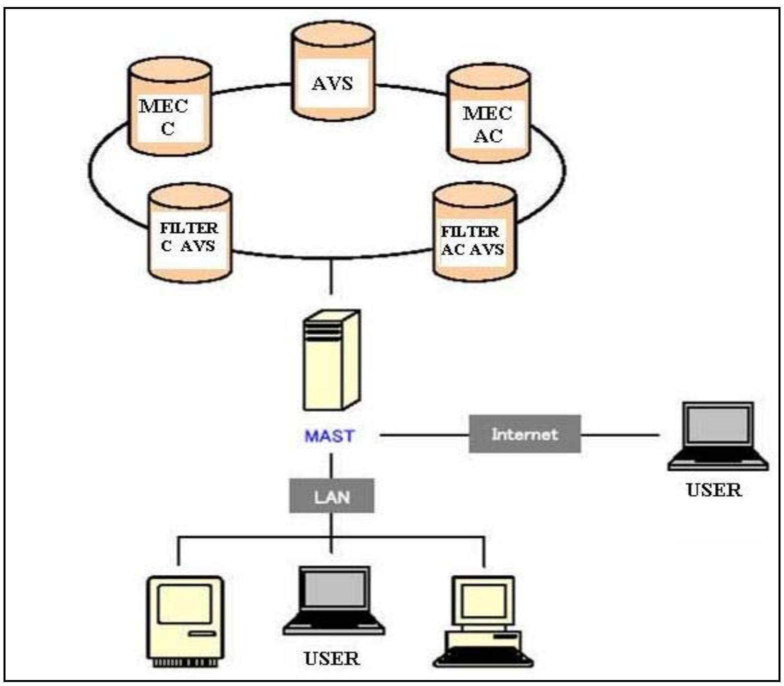

Figure 5: MEC online computation [6]

MAST web application server is the software which has a function to control the interaction among computation programs. The MEC main program is MEC hydrostatic model variable mesh as known as the MEC-C program. AVS Express version 6 is the graphical software that is produced by Advanced Visual System

Inc., and visualizes the results from the program Filter C-AVS and Filter AC-AVS.

3.2 Potential Theory

Surge forces, that acts on the FPSO for two conditions (with/without submerged plate) [7], are computed by using 2D boundary element method based on potential theory and use the coordinate system as shown in Figure 6.

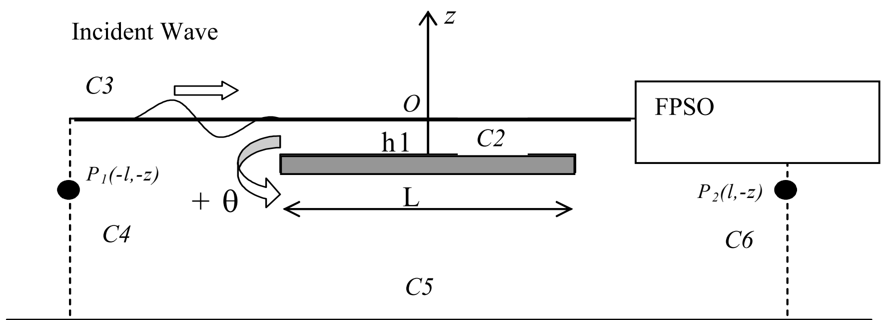

Figure 6: Coordinate system

Two imaginary boundaries are assumed to be located far away from FPSO *x=l* (boundary *C6*) and *x=-l* (boundary *C4*). Since the fluid is inviscid and incompressible, and the flow is irrotational, the velocity potential satisfies the Laplace equation in the whole domain. The velocity potential must also satisfy the following boundary conditions: two imaginary boundaries (*C4,C6*), bottom surface (*C5*), water free surface (*C3*), submerged plates and FPSO's wetted surfaces (*C1,C2*). By assuming *P* as point in fluid field and *Q* as point in boundary in the Green Formula, so that the radiation boundary value problem (bvp) can be defined as:

$$\alpha\phi_l(P) = \oint_C \frac{\partial \phi_l(Q)}{\partial n}\ln(1/r)ds - \oint_C \phi_l(Q)\frac{\partial}{\partial n}(\ln(1/r))ds \qquad (3)$$

where:*C=C1+C2+C3+C4+C5+C6*; the boundaries at the closed domain, *r* is distance between *P* and *Q*, α is radian measure, when *P* is on the boundary $\alpha=\pi$.

The Equation (3) can be discretised by dividing the boundary of domain into number of line elements. The velocity potential at an element is expressed in term of its nodal potential value by using linear shape function. The boundaries *C1 – C6* are divided into the number of elements *NE1 – NE6*, respectively. In the numerical computation the numbering of the element on the boundary is in an anticlockwise direction. By substituting the linear shape function into Eq.(3), the discrete bvp is obtained. Let put the boundary conditions into the discrete bvp, the radiation velocity potential at each point hence solved. The surge forces E_k in Equation (4) at FPSO are obtained by applying Haskind Relationship of the incident and radiation velocity potential, and consider the diffraction problem on the wetted surface boundary conditions on FPSO (*C1*).

$$E_k = -i\rho\omega \int_{C2} \left(\phi_0 \frac{\partial \phi_k}{\partial n} + \phi_k \frac{\partial \phi_0}{\partial n} \right) ds \tag{4}$$

4.0 RESULTS AND DISCUSSION

4.1 Wave transmission and reflection of plate

Figures 7 and 8 are the output from MEC online computation that show the performance and flow mechanism of the particle waves at full-scale period 7 seconds without and with the submerged plate on location, respectively. The figures show clearly the differences of the vector velocity of the particle wave where the submerged plate is not and on location. The velocity increases on two surfaces' submerged plate and the flow below the plate start to return at the end of plate and opposite the direction of the flow on top surface. These two flows make a clash on top surface, and form a steep slope wave.

Figure 8 indicates the wave length at the lee side of the submerged plate is shorter than the incident wave; as well the wave amplitude is smaller.

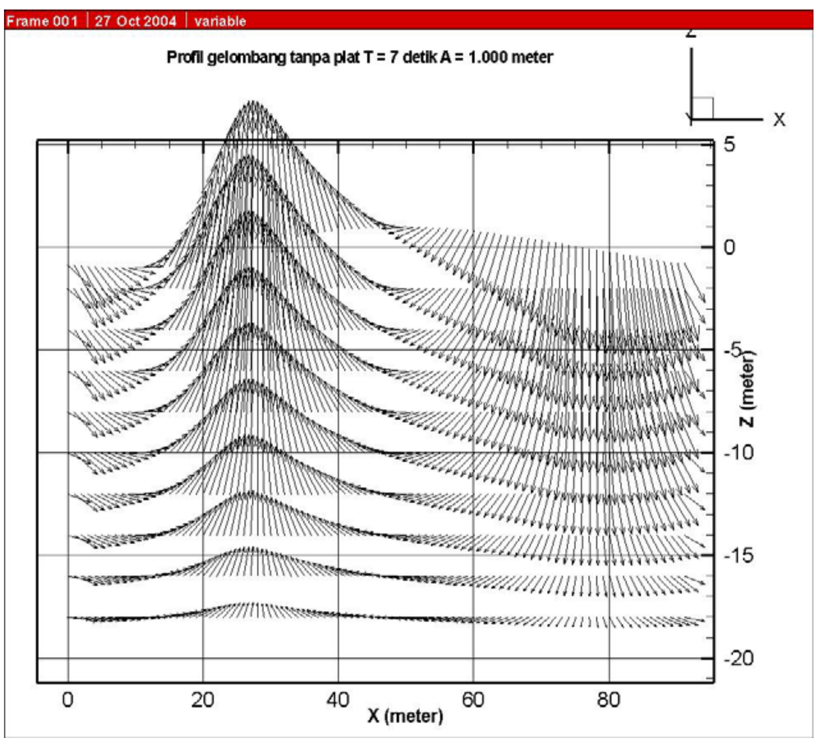

Figure 7: Vector velocity wave particle at T=7sec

Data for each model test run were acquired for a total duration of 30 secs. As shown in Figure 9 at a sampling frequency of 50 Hz. Waves were generated for a total duration of 60 s. Depending upon the period of wave generated, data collection commences 30–65 s after starting the wave generation. This is to make sure that the data collection is started only after repeatability of the same wave heights at the model location is established. The starting time for data collection is set based on trial runs with different periods of waves. The data collection duration is set at 30 s, based on the following criteria:

1. The regular wave time series should have at least 10 wave cycles.
2. The data collection must be completed before any reflected waves, either from the wave maker or from the beach, affect the measurements around the test section.

The tests data were analyzed by using Fourier series method.

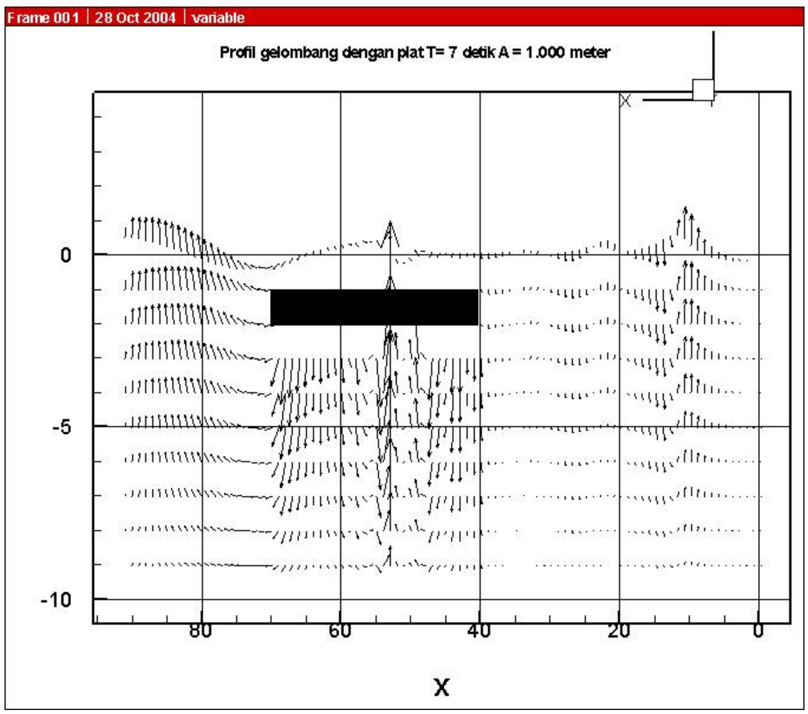

Figure 8: Vector velocity wave particle on submerged plate at T=7 sec

Figure 10 shows the transmission coefficient C_t of the selected plate sizes and it is compared with the MEC online computation. It proves that the average transmission coefficient for the range of period 4 till 12 secs. is about 0.4 as the chosen coefficient in the curve design. From the comparison, the MEC online computation on first component of transmission wave agrees well with the model tests.

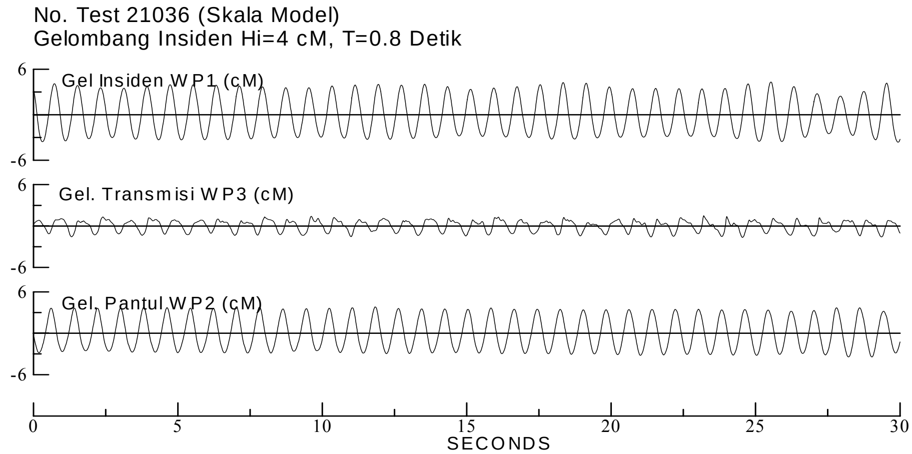

Figure 9: Model tests data at T=0.8s (full-scale T=5.7s) for incident, transmission and reflection wave

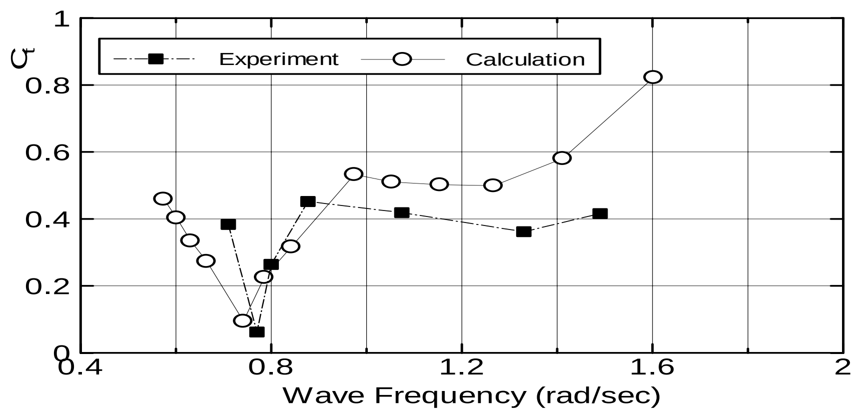

Figure 10: First component in fourier series of transmission wave

4.2 Surge Forces on Floating Structure at the Lee Side of Plate

The source code of 2D boundary element method was validated to calculate hydrodynamic forces on a square submerged plate in infinite fluid domain. The hydrodynamic forces computation on heave added mass (M_H) of the square plate is shown in Figure 11, in the same figure the other method is shown for comparison.

Figure 12 shows the computation on the selected submerged plate with variation effects of the inclination angle on the surge forces F_x . The results are made in nondimensional forces. The figure show that the minimum surge forces on the plate occurs at the angle = 0 deg (horizontal plane).

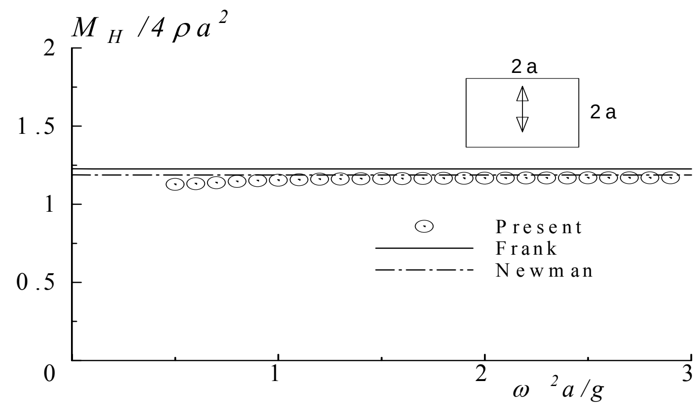

Figure 11: The validation check on 2D BEM code

In the model tests to measure the surge forces on the FPSO, Figure 13 shows an example of capturing data on wave height and surge forces of FPSO in irregular wave using the Jonswap spectra with Hs=2 m and Tp=11secs.

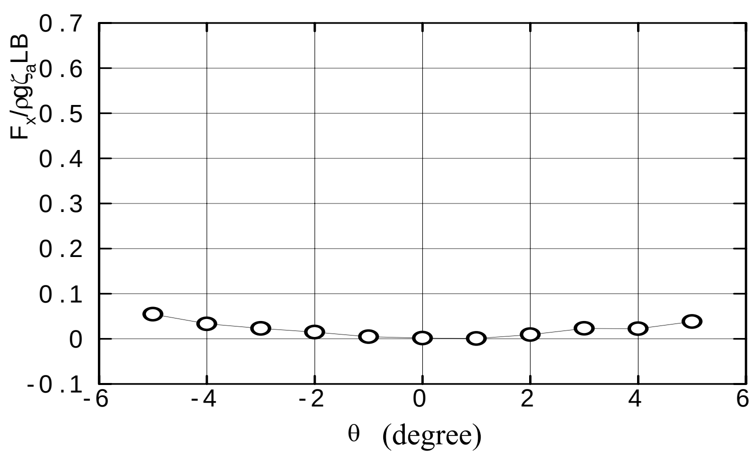

Figure 12: Effect of inclination angle of plate on the surge forces in wave period 7 secs

Figure 14 shows the surge forces results on FPSO for two conditions, namely freely floating and at the lee side of the submerged plate. The computations using 2D BEM are also shown in the same figure for comparison. The computation results have similar tendency with the model tests both for two conditions. It is found that the surge forces on FPSO at the lee side of the submerged plate reduce at low incident wave below 1 rad/sec. Moreover at high wave frequencies, the surge forces of FPSO are same as the freely floating condition. On the other word the incident wave does not reduce at the submerged plate.

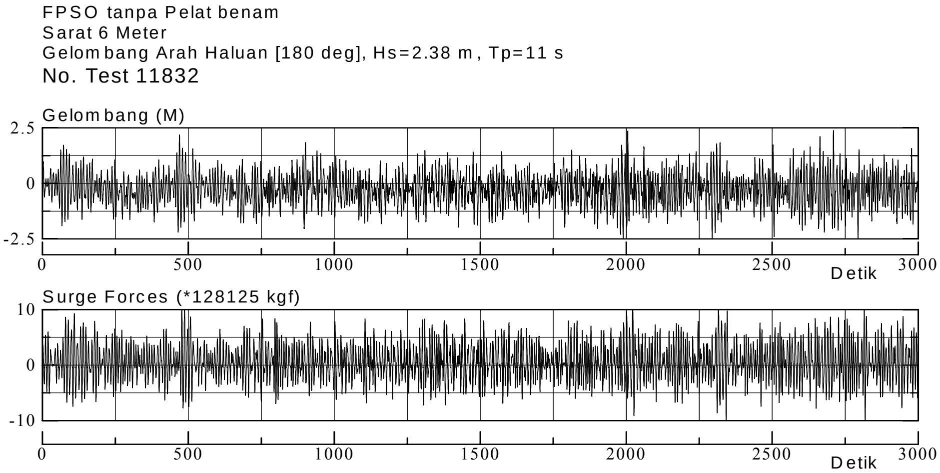

Figure 13: Time histories of surge forces of FPSO in irregular waves

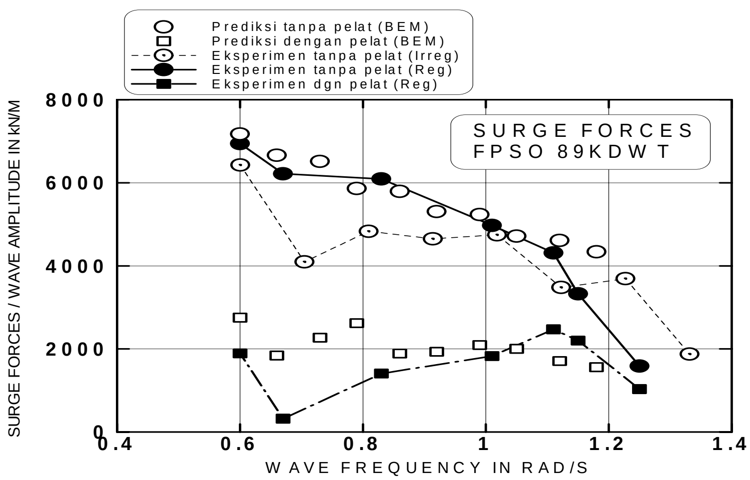

Figure 14: Surge forces of FPSO at the lee side of (with) the submerged plate

5.0 CONCLUSION

When the waves approach the plate, the wave particles flow velocity increase on the two surfaces (top and base). The base flow returns at the end of plate and clashes with the top flow, hence it forms a steep slope wave at water surface.

The MEC online computations on the first component transmission wave have agreed well with the model tests. The transmission coefficient for the selected submerged plate is about 0.4 in period range of 4 till 12 secs. The inclination effect on the surge force of the submerged plate is small. The minimum surge force of the plate occurs at the angle of inclination = 0 degree.

The wave exciting surge forces of the FPSO at the lee side of the submerged plate have been examined by using 2D Boundary Element Method based on the potential theory. By comparing the numerical computations with the tests data, the results show that the numerical results have similar tendency to the experimental, and it is deduced that the submerged plate reduces the wave exciting surge forces effectively at low wave frequencies.

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