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ESTIMATION OF SWAY, HEAVE AND ROLL OF A MOORED FLOATING BREAKWATER DUE TO INTERACTION WITH WAVES

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ABSTRACT

Floating breakwaters offer an alternative to conventional fixed breakwaters and usually preferred in relatively low wave energy environments or where water depth or foundation considerations preclude the use of a bottom-founded structure. In this study a two-dimensional numerical model has been developed that simulates the dynamic displacements, i.e., sway, heave and roll of a moored floating body under wave action. The model is based on the coupling of SOLA-VOF (Volume Of Fluid) method and porous body model. A pontoon type submerged floating breakwater of rectangular shape supported by mooring chain is considered in the model. The SOLA scheme is employed to calculate the pressure and velocities in each time step and the added dissipation zone method is adopted to treat the open boundary. The analysis is done for both the vertical and inclined mooring lines alignments. It is assumed the weight of the floating body is much less compared to the buoyancy force acting on it, so that there does not occur any slack state in the mooring lines during the course of wave interaction. Considering this assumption, in case of vertical mooring lines alignment, the roll motions of the body can not occur and only sway and heave displacements are seen. On the other hand, all three displacements develop when the floating body is moored by the inclined mooring lines and the above assumption is still considered. The model simulations of the dynamic displacements of the floating body are compared with the data measured through laboratory experiment. The very good agreement between the simulated and measured data demands the successful performance of the developed numerical model.

Keywords : *VOF method, dynamic displacements, floating breakwater.*

1. INTRODUCTION

Floating breakwater can be considered as an alternative solution to conventional fixed breakwaters in coastal areas with mild wave conditions. In the last years, an evolution of the floating breakwater was seen both regarding the largest structures protecting big harbors and the smaller ones defending craft harbors or marinas. They have been adopted at number of sites where water depth or other constraints render the rubble mound and caisson structures too costly. They are environmentally advantageous because they produce minimal interference on water circulation, sediment transport, and fish migration. They are more adaptable to the water level changes that occur at harbors that are built on reservoirs and in coastal areas having a large tidal range. As a result of all these positive effects, many studies have been carried out to investigate the hydrodynamic performance of these floating breakwaters. Several types of floating breakwaters have been developed, however, the most commonly used type of floating breakwaters is the one that consists of rectangular pontoons connected to each other and moored to the sea bottom with cables or chains. Many studies have been involved in floating breakwaters to investigate their performance, mooring forces, and motion responses. Adee (1975) developed a two-dimensional linear theoretical model to predict the performance of catamaran type floating breakwaters in deep water and compared the results with measurements in a model tank and from a prototype installation in the field. Yamamoto et al. (1980) solved the problems of wave transformation and motions of elastically moored floating objects by the direct use of Green's identity formula and validated their solutions with experimental investigations. They found that if the mooring system is properly arranged, the wave attenuation by a small draft breakwater can be improved moored. Isaacson and Byres (1988) reported the development of a numerical model, based on linear diffraction theory, to investigate floating breakwater motions, transmission coefficients, and mooring forces, in obliquely incident waves. Sen (1993) developed a numerical method to simulate the motions of two-dimensional floating bodies. Sannasiraj et al. (1998)

adopted a two-dimensional finite element model to study the behavior of pontoon-type floating breakwaters in beam waves. Williams et al. (2000) investigated the hydrodynamic properties of a pair of long floating pontoon breakwaters of rectangular section. Lee and Cho (2003) developed a numerical analysis using the element free Galerkin method and mainly concerning the influence of mooring line condition on the performance of floating breakwater. Seah and Yeung (2003) have studied the sway and roll hydrodynamics of cylindrical sections. In this study, a two-dimensional numerical model is proposed that combines the VOF method and the porous body model to simulate the nonlinear wave interaction with the floating body. A rectangular shaped pontoon type submerged floating breakwater supported by mooring chain is considered in the model. The alignment of mooring chains is considered for both vertical and inclined directions. The dynamics of the body is calculated considering its time-marching finite displacements. The time-marching boundary conditions enable it to consider the non-linear dynamic interaction between the waves and the floating body.

2. NUMERICAL MODELING

The numerical model consists of the continuity equation, the Navier-Stokes equation for incompressible fluid and the advection equation that represents the behavior of the free surface. The two-dimensional numerical domain is divided into staggered meshes in both horizontal (*x*-axis) and vertical (*z*-axis) directions. As there occurs the dynamic displacements (sway, heave and roll) of the breakwater due to wave action, the numerical cells can be classified into five types; a full cell filled with fluid, an empty cell occupied by air, a surface cell containing both fluid and air, an obstacle cell that represents the structure and the porous cell containing the fluid, the structure and/or air. So the continuity equation, Navier Stokes equations and the VOF function equation should be modified as below considering the effects of γ_x, γ_z and γ_v, where γ_x and γ_z represent the ratio of the permeable length to the cell length in vertical and horizontal directions respectively and γ_v represents the ratio of the permeability volume in a cell.

The continuity equation is,

$$\frac{\partial(\gamma_x u)}{\partial x} + \frac{\partial(\gamma_z w)}{\partial z} = q(x,z,t) \tag{1}$$

$$q(x,z,t) = \begin{cases} q^*(z,t) \ldots\ldots\ldots\ldots\ldots\ldots x = x_s \\ 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots : x \neq x_s \end{cases} \tag{2}$$

where u and w are the flow velocity of x and z direction respectively, q is the wave generation source with q^* as the source strength which is only located at $x = x_S$ and t is the time.

The Navier-Stokes equations,

$$\gamma_V \frac{\partial u}{\partial t} + \gamma_X u \frac{\partial u}{\partial x} + \gamma_Z w \frac{\partial u}{\partial z} = -\frac{\gamma_V}{\rho}\frac{\partial p}{\partial x} + \upsilon\left[\frac{\partial}{\partial x}\left\{\gamma_X\left(2\frac{\partial u}{\partial x}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_Z\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\}\right] \tag{3}$$

$$\gamma_V \frac{\partial w}{\partial t} + \gamma_X u \frac{\partial w}{\partial x} + \gamma_Z w \frac{\partial w}{\partial z} = -\frac{\gamma_V}{\rho}\frac{\partial p}{\partial z} + \upsilon\left[\frac{\partial}{\partial x}\left\{\gamma_X\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_Z\left(2\frac{\partial w}{\partial z}\right)\right\}\right] + \frac{1}{3}\upsilon\frac{\partial q}{\partial z} - \gamma_V g \tag{4}$$

where p is the pressure, υ is the kinematic viscosity, ρ is the fluid density and g is the gravitational acceleration.

The advection equation of VOF function F,

$$\gamma_v \frac{\partial F}{\partial t} + \frac{\partial(\gamma_x u F)}{\partial x} + \frac{\partial(\gamma_z w F)}{\partial z} = Fq \tag{5}$$

As suggested by Brorsen and Larsen (1987), the flux density of wave generation source q is gradually intensified for initial three wave periods from the start of computation for stable wave generation. The mesh sizes are used as Δx = 2 cm and Δz = 1 cm. An added dissipation zone method is used to treat the open boundaries. The pressure in the full cell can be calculated by means of the SOLA scheme. It is considered that the floating body is of very light weight compared to the buoyancy forces acting on it vertically. This assumption results no slack state in the mooring lines that causes no impulsive force on it. The dynamics of the floating body due to wave action are calculated as shown in Fig. 1. The horizontal displacement (sway), vertical displacement (heave) and the rotational movement (roll) of the body are calculated with respect to its center of gravity. The wave forces acting on the body H3, H4, H5, H6, V3, V4, V5, and V6 are calculated by integrating forces acting on the respective surface of the body which are estimated from the pressure of the respective cells. Applying the Newton's second law, the horizontal motion equation of the body can be written as below:

$$\sum F_X = m.a_x$$

$$or,\ H3 + H5 - H4 - H6 - 2.T3\cos\theta 3 + 2.T4\cos\theta 4 = ma_X \tag{6}$$

where, a_x denotes the acceleration of the body in horizontal direction and T3 and T4 represent the offshoreside and onshoreside mooring force respectively

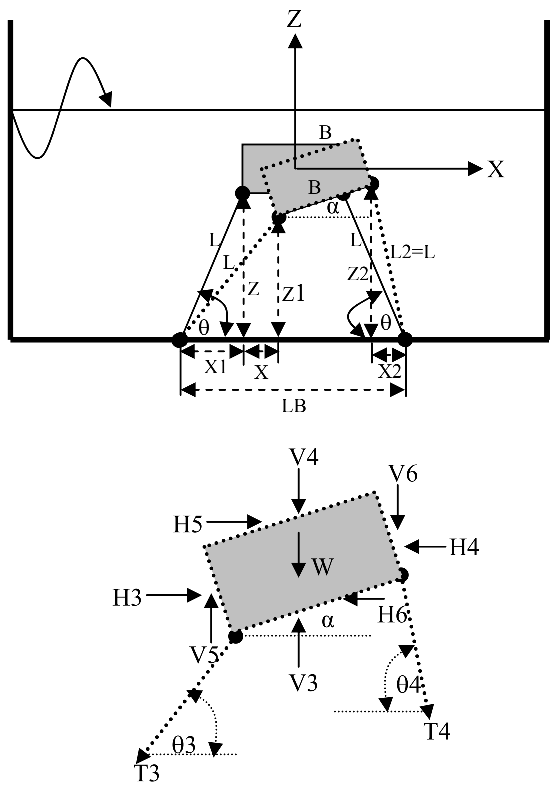


Fig. 1 Calculation of floating body dynamics

The similar equation for vertical motion of the body can be written as below:

$$\sum F_Z = m.a_z$$

$$or,\ V4 + V6 + W - V3 - V5 + 2T3\sin\theta3 + 2T4\sin\theta4 = m.a_z \quad (7)$$

where, a_z denotes the acceleration of the body in vertical direction and W is the weight of the body.

Again, the rotation of the body is governed by the moments acting on the body. Taking the moment acting of the center of gravity of the body in anti-clockwise direction, following equation is found.

$$\sum M_{Cg.X} + \sum M_{cg.Z} + \sum M_{cg.T} = I\alpha \quad (8)$$

where, $\sum M_{Cg.X}$, $\sum M_{Cg.Z}$, $\sum M_{Cg.T}$ represent the summation of moment governed by the horizontal wave forces, vertical wave forces and the mooring lines forces respectively, I is the mass moment of inertia of the body and α is the roll displacement of the body. Also, considering no slack condition, from the geometry of the Fig. 1, we write Eq. (9) and (10).

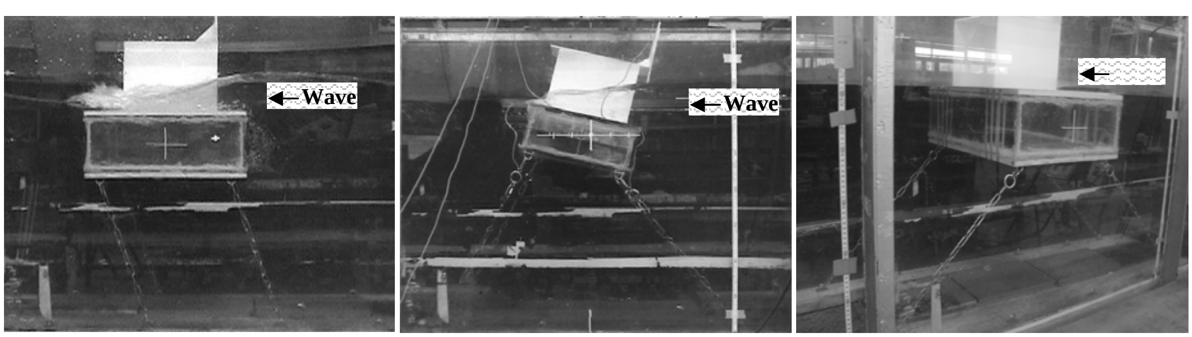
$$Z1 = \sqrt{L^2 - (X1 + X)^2} \quad (9)$$

$$(LB - X1 - X - B\cos\alpha)^2 + (Z1 + B\sin\alpha)^2 = L^2 \quad (10)$$

By solving above five simultaneous equations (Eq. (6) to Eq. (10)), the unknown parameters a_x, a_z, α, T3 and T4 are calculated. Finally the sway and heave displacements are estimated using a_x and a_z values. Mizutani et el. (2004) developed a VOF simulation model to study the dynamics of the floating breakwater considering finite displacement. They solved the dynamics equations explicitly and the model considers only vertical moorings. In the present model, we consider both vertical and inclined mooring alignments and the simultaneous equations are solved implicitly.

3. LABORATORY EXPERIMENT

A laboratory experiment is done in a two-dimensional wave tank of 30 meters long, 0.7 meter wide and 0.9 meter of height. The floating body is made of acrylic material with vacuum inside. The body is 40 cm long, 68 cm wide and 18 cm of height. The body is anchored to the bottom of the tank by chain with three different inclinations - vertical (θ= 90˚) and two inclined (θ= 60˚ and θ= 45˚). Photo view of the all three types connections are shown in Fig.2. The floating body is always anchored so that its top surface was at the height of 62 cm from the bottom of the wave tank. Water depth in the wave tank was varied as 62 cm, 65 cm and 68 cm. Regular waves are generated from the wave generator and the wave steepness (H/L) is varied as 0.01,0.02 and 0.03.



(a) (b) (c)

Fig. 2 Photo view of the floating body dynamics at the wave tank during experimental run (a) vertical mooring, θ=90º (b) inclined mooring, θ=60º (c) inclined mooring, θ=45º.

The experiments are conducted for the waves of ten different wave periods, i.e., T=0.8 sec,0.9 sec, 1.0 sec,1.1 sec, 1.2 sec,1.3 sec, 1.4 sec, 1.6 sec,1.8sec and 2.0 seconds. During the experiment, sway (Δx), heave (Δz) and the rolling (α) of the body occurs due to the wave action. These displacements of the floating body are recorded with the laser system. Two vertical laser rays and two horizontal laser rays are focused on a white paper box that is set up at the top surface of the floating body. When the floating body moves due to the wave action, the box also moves and the corresponding displacements are recorded with the laser system. The rolling (α), sway (Δx) and heave (Δz) of the floating body are calculated using the laser system data.

4. RESULT AND DISCUSSION

4.1 Experimentally measured displacements of the floating body

Due to wave action, there occur three displacements of the body - heave (Δz), sway (Δx) and rolling (α) for inclined moored condition. These displacements are shown in Fig. 3 for the condition of floating body anchored with bottom of the tank

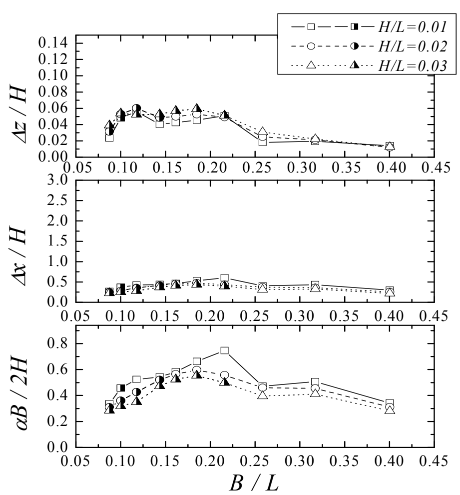


Fig. 3 Relative displacements of the floating body (θ=60º, h=68cm)

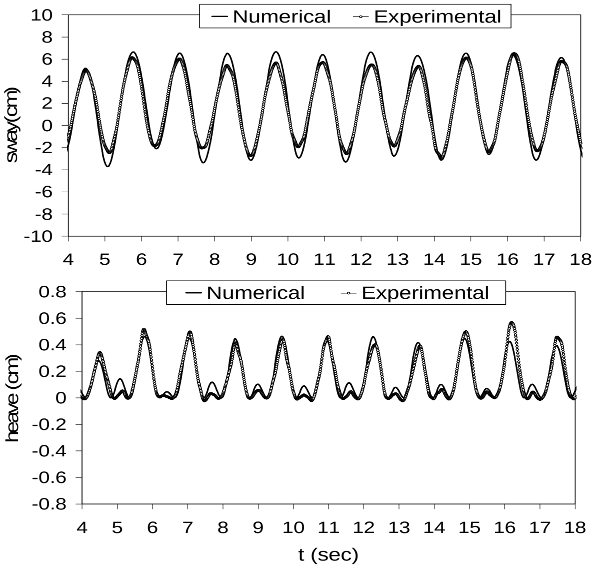
with 60˚ inclination and 6 cm submergence depth (h=68 cm). The half-filled symbols in the figure represent the wave breaking over or behind the floating body. It is seen that wave breaking occurs up to the value of B/L=0.22 for wave steepness H/L=0.03 and up to the less value of B/L for wave steepness 0.01 and 0.02. The effects of wave steepness (H/L) on these displacements are also shown in the figure. This rolling motion of the body makes it tilted and causes its top surface inclined that result it acts as a wave absorber of the incoming waves. Moreover, during the experiment, it is observed that the wave breaks over the top surface of the inclined floating body during its anticlockwise rotational motion. On the other hand, during the clockwise rotational motion of the floating body, its top surface becomes sloped to the onshore side, but at the same time its offshore side vertical surface becomes sloped that also encourages the wave breaking resulting wave energy dissipation.

4.2 Comparison between measured and simulated motion responses of the floating body

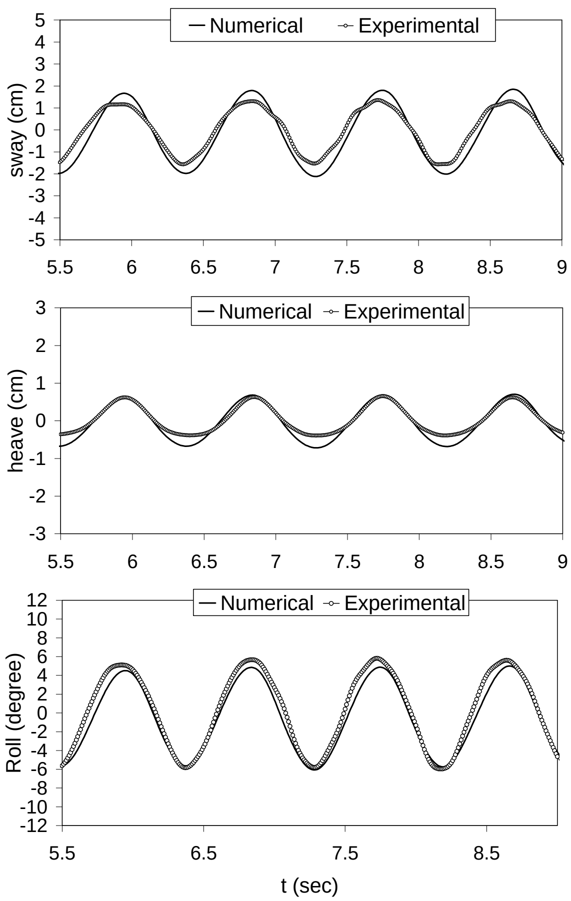
The developed numerical model can simulate well the motion responses of the floating breakwater due to its interaction with wave. The time series numerical results of the displacements of the breakwater are verified with measured results from the recorded laser displacement sensors data during the experiment, which are presented in Fig. 4. In case of the mooring lines anchored vertically (θ=90º) (Fig. 4a), it is observed that there occurs no roll displacement of the body and only the sway and heave values are shown in the figure. For inclined mooring with θ=45º (Fig. 4b), sway, heave and roll are observed and shown in the figure. The positive sway magnitudes represent the horizontal displacements of the floating body along the onshoreward, i.e., along the direction of positive *x*-axis. On the other hand, the negative sway magnitudes represent the horizontal displacements of the floating body along the offshoreward which is along the direction of negative *x*-axis. The positive heave values represent its displacement along the downward direction and the negative heave values represent its displacement along the upward direction. The anticlockwise rotation of the body is assigned as positive roll and clockwise rotation is defined as negative roll in the figure. The comparison shows good agreement of the numerical simulation results compared to measured data.

5. CONCLUSIONS

A two-dimensional numerical estimation method for calculating dynamics of a pontoon type moored floating breakwater under wave action is developed. The model couples the VOF method with porous body model. SOLA scheme with the wave generation source method and the added dissipation zone method has been applied. The model can simulate the floating body dynamics for both vertical and inclined alignments of the mooring lines. The model results are varied with the experimentally measured data. The good agreement between the numerical and experimental results regarding the dynamic displacements of the floating body (sway, heave and roll) confirms the validity of the developed numerical model.



(a)



(b)

Fig. 4 Comparison of numerical and experimental results of the time series values of displacements of floating body (a) H=7.3 cm, T=1.3 sec, h=65cm, θ=90º (b) H=3.8 cm, T=0.9 sec, h=65 cm, θ=45º

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