A Numerical Study on Pontoon Type Floating Breakwaters in Oblique Waves

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ABSTRACT: A numerical investigation was made to examine characteristics of rectangular pontoon type floating breakwaters in oblique waves. Sway and heave wave exciting forces, roll moment acting on the floating breakwater and three motion responses decrease as the incident wave angle increases for the most of the wave ranges. There exists a minimum wave transmission coefficient which is a function of wave frequency. In short wave range wave transmission coefficient increases as the incident wave angle increases. In long wave range, however, wave transmission coefficient decreases as the wave incident angle increases.

KEYWORDS: Floating Breakwater, Wave Transmission Coefficient, Oblique Waves

1. Introduction

As exploitation of ocean or coastal waters becomes more frequent, people have been paying much attention to floating breakwaters. Since they have some advantages over conventional fixed type breakwaters, they give less impact on the ocean environment. They do not interfere the natural water exchanges, since the floating breakwaters allow the ocean current pass under the structure. The construction cost is less expensive and the construction period is relatively short. Especially the construction cost does not increase much as the water depth increases, while construction cost of the conventional fixed breakwater increases dramatically if the water depth is greater than 15-20m. Following McCartney [1982] if water depth is in excess of 6m, the floating breakwater is cost effective. Ginger [1984] reported the construction of the floating breakwater at Town Quay in England. The length of the breakwater is 205m and the construction period was only 6 months. It costed $5,000/m, while the construction cost of the conventional fixed breakwater was estimated $7,500 - 10,000/m. Sugarawa and Yoshimura [1984] reported an successful installation and operation of 270m long floating breakwater in Fukuyma port in Japan.

There have been numerous investigations made for various floating breakwaters. McCartney [1982] reviewed various types of floating breakwaters and provided information about installation and design consideration. See also Ghilman [1988] for a review of some practical aspects of floating breakwater design. One disadvantage of the floating breakwater is that it partially transmits the waves, although this is a major advantage in different point of view. In order to fully exploit the advantages of the floating breakwaters, one has to improve the performance especially for the long waves. Therefore there have been a lot of researches to improve the performance of the floating breakwaters (Kinoshiba and Saiki [1981], Mooney et al. [1995], Mani [1991], Chishiri and Kashiwagi [1991], Nakato and Kikumai [1980], Song et al. [1988] and Kim et al. [1988]).

One of the most important parameter in the floating breakwater design is a wave transmission coefficient which is a height ratio of transmitted and incident wave. Wave transmission coefficient is a function of incoming wave frequency, water depth, floating breakwater geometry, mooring system and so on. Usually the wave transmission coefficient is understood in two dimensional sense. However the wave transmission coefficient will vary according to the incident wave angle.

2. Formulation

Let us assume that the fluid is inviscid, incompressible and the flow is irrotational. The amplitude of the incident wave is assumed to be small. Then we can use linear potential theory. Cartesian coordinate system is used and the vertical z direction is pointing upward. Undisturbed free surface is located at z = 0. The velocity potential satisfies the Laplace equation.

$$\nabla^2 \Phi (x, y, z, t) = 0$$  \hspace{1cm} (1)

At the body boundary following conditions must be satisfied.

$$\nabla \Phi \cdot \vec{n} = \nabla \cdot \vec{V}$$  \hspace{1cm} (2)

where \( \vec{V} \) is the velocity vector of the body and \( \vec{n} \) is a normal vector on the body whose positive direction is outward the fluid domain.

Besides the Laplace equation and the body boundary condition, the velocity potential also satisfies the free surface boundary condition, bottom boundary condition and the proper radiation conditions.
Using the linearity of the velocity potential one can decompose the velocity potential using the incident potential $\Phi_i$, the diffraction potential $\Phi_D$, and the radiation potential $\Phi_R$ as follows.

$$\Phi = \Phi_i + \Phi_D + \Phi_R$$

(3)

Then on the body following condition must satisfy

$$\frac{\partial \Phi_D}{\partial n} + \frac{\partial \Phi_D}{\partial z} = 0,$$

(4)

$$\frac{\partial \Phi_R}{\partial n} = \nabla \cdot \vec{n}$$

Let us consider a long cylinder parallel to $y$-axis. A monochromatic wave of frequency $\omega$ and wave number $k$ approaches the floating breakwater with an angle $\delta$. When $\theta$ is zero, it represents pure beam sea. We assume that the motion is small and time harmonic. Following Liu and Abbaspour [1962], one can write the velocity potential as follows using the uniformity in $y$-direction.

$$\Phi(x, y, z, t) = \text{Re} \left\{ \phi(x, z) e^{-i(\omega t - \beta y)} \right\}$$

(5)

where $\beta = k \sin \theta$.

The complex velocity potential $\phi$ can be decomposed into three complex potentials.

$$\phi(x, z) = \phi_i + \phi_D + \phi_R$$

(6)

The incident wave potential in complex form can be written by following equation.

$$\phi_i = -\frac{ig A}{\omega \cosh h(z + k)} e^{i\omega x}$$

(7)

$$\omega^2 = gh \tanh hb, \quad k^2 = \omega^2 + \beta^2$$

(8)

where $A$ is the incident wave amplitude, $h$ is water depth and $k$ is the wave number.

The diffraction potential $\phi_D$ must satisfy following boundary value problem which is two dimensional in nature.

$$\nabla^2 \phi_D(x, z) = i \beta \phi_D = 0 \text{ in the fluid domain}$$

(9)

$$\frac{\partial \phi_D}{\partial z} - \omega^2 \phi_D = 0 \text{ on } z = 0$$

(10)

$$\frac{\partial \phi_D}{\partial n} = -\frac{\partial \phi_D}{\partial n} \text{ on the body}$$

(11)

$$\frac{\partial \phi_D}{\partial z} = 0 \text{ on the bottom}$$

(12)

$$\lim_{z \to -\infty} \left( \frac{\partial}{\partial x} + i \alpha \right) \phi_D = 0$$

(13)

The motion of the body can be expressed as follows.

$$x_i(t) = \text{Re} \left\{ \xi_i e^{-i\omega t} \right\} \text{ for } j = 1, 2, 3$$

(14)

where $x_i$ represents displacements of sway, heave and roll for $j=1,2,3$ respectively, and $\xi_i$ represents corresponding complex displacements.

Since the motion is small and sinusoidal, one can decompose the radiation potential as follows.

$$\Phi_R = \text{Re} \{ \xi_i e^{-i\omega t} \} \text{, for } j=1,2,3$$

(15)

where $\phi_i$ represents the complex potential of each mode. Using eq. (14) and (15) we can express the radiation boundary value problem for each $\phi_i$, as follows.

$$\nabla^2 \phi_i(x, z) - \beta^2 \phi_i = 0 \text{ in the fluid domain}$$

(16)

$$\frac{\partial \phi_i}{\partial z} - \omega^2 \phi_i = 0 \text{ on } z = 0$$

(17)

$$\frac{\partial \phi_i}{\partial n} = -i\omega n_i \text{, for } j = 1, 2, 3 \text{ on the body}$$

(18)

$$\frac{\partial \phi_i}{\partial z} = 0 \text{ on the bottom}$$

(19)

$$\lim_{z \to -\infty} \left( \frac{\partial}{\partial x} + i \alpha \right) \phi_i = 0$$

(20)

where $n_i$ is the extended normal vectors defined by following equation.

$$n_1 = n_x, \quad n_2 = n_y, \quad n_3 = xn_z - zn_x$$

(21)

Once we obtain the diffraction potential, the forces and the moment acting on the body due to wave can be calculated from the following equation.

$$F_i = i \omega \rho \int \phi_i \phi_d(x, z) n_i \, ds$$

(22)

where $\rho$ is the fluid density.

After solving radiation boundary value problem, hydrodynamic coefficients can be calculated using following equations:

$$\mu_i = -\frac{\rho}{\omega} \int \text{Im} \{ \phi_i \} n_i \, ds$$

(23)

$$\lambda_i = \rho \int \text{Re} \{ \phi_i \} n_i \, ds$$

(24)

Assuming that the incident waves are regular, we can write the equation of the motion of the floating breakwaters in the frequency domain as follows.

$$\sum_i \left[ (B_i + K_i) - \omega^2 (m_i + \mu_i) - i \omega \lambda_i \right] \xi_i = f_i$$

(24)
stiffness matrix, $K_D$ the mooring stiffness matrix.

After solving the diffraction and radiation problems and the equation of motion, the total velocity potential is given by the following equation.

$$
\Phi = \text{Re} \left( \phi_1^+ + \sum_{m=1}^{\infty} \xi_m e^{i \kappa_m (z - h)} \right)
$$

(25)

Then the free surface profile can be calculated as

$$
\eta(x, t) = -\frac{1}{g} \frac{\partial \Phi}{\partial t} \bigg|_{z=0}
$$

(26)

The wave transmission coefficient $C_T$, which is an amplitude ratio of transmitted and incident waves, is defined by following equation.

$$
C_T = \frac{A_0^+}{A_0^-}
$$

(27)

where $A_0^+$ is the wave amplitude at far downstream.

3. Numerical Calculation

The boundary value problems described by equations (9)-(13) and (16)-(20) can be solved by a boundary element method. The fundamental solution for the two-dimensional Helmholtz equation is given by

$$
G = -K_0(\mu r)
$$

(28)

$$
r = \sqrt{(x-x_0)^2 + (z-z_0)^2}
$$

where $K_0$ is the modified Bessel function of the second kind and $r$ is the distance between a boundary point $(x, z)$ and a source point $(x_0, z_0)$. Using the Green's second identity and the fundamental solution, we can obtain the following integral equation.

$$
\left( \frac{2\pi}{\sigma_i} \right) \phi_i = \int_{\Gamma} \left( \phi \frac{\partial G}{\partial n} - G \frac{\partial \phi}{\partial n} \right) d\Gamma
$$

(29)

where $2\pi$ is used for internal points and $\sigma_i$ for boundary points.

Since eq. (28) only satisfies the governing equation, one has to distribute the singularities through the whole boundaries. In order to make the computation efficient we introduce matching boundaries. The general solutions which satisfy the governing equation and all the boundary conditions including the radiation conditions outside the matching boundaries are known. The solutions of the outer region may be written as

$$
\phi^+ = A_0^+ W_0^+ + \sum_{m=1}^{\infty} A_m^+ W_m^+
$$

$$
\phi^- = A_0^- W_0^- + \sum_{m=1}^{\infty} A_m^- W_m^-
$$

(30)

$$
\phi^+ = A_0^+ W_0^+ + \sum_{m=1}^{\infty} A_m^+ W_m^+ = \frac{1}{g} \frac{\partial \Phi}{\partial t} \bigg|_{z=0}
$$

$$
\phi^- = A_0^- W_0^- + \sum_{m=1}^{\infty} A_m^- W_m^-
$$

where

$$
\omega^2 = g \tanh kh
$$

$$
\omega^2 = g k_s \tan k_s h
$$

(31)

$$
W_0^+ = e^{i \alpha x} \frac{\cosh k(x + h)}{\cosh kh}
$$

$$
W_0^- = e^{i \alpha x} \frac{\cosh k(x + h)}{\cosh kh}
$$

(32)

Here $k_o$ is a free wave number and $k_s$'s are local wave numbers.

At the matching boundary we impose following conditions.

$$
\phi = \phi^+ \quad \frac{\partial \phi}{\partial n} = \pm \frac{\partial \phi}{\partial n} \bigg|_{x = x^-}
$$

(33)

For numerical computations, the infinite series in eq. (30) are truncated into finite series and the number of unknown coefficients must be the same as that of the nodes on the matching boundary.

4. Result and Discussion

In order to examine the effect of the wave incident angle on the breakwater performance, four wave incident angles ($\theta = 0, 45, 60,$ and $75$ degrees) are selected for computation. Mooring stiffness is chosen based on the computation by Kim et al (1998).

Because the effect of the incident wave angle, which is a three dimensional characteristic in nature, is expressed in terms of two dimensional governing equation, the velocity potential in this formulation varies as the wave incident angle changes.

Figure 1 shows non-dimensional horizontal wave force according to each incident wave angle $\theta$. When $\theta$ is zero, this figure shows a typical form of two dimensional force. In this figure we can see that the horizontal force acting on the floating breakwater decreases as $\theta$ increases.

![Fig. 1 Non-dimensional horizontal wave forces $F_x = F_x/0.5p$](image)

$gBA$ $B/D = 2.67$, $h/D = 3.0$. 

\[ gBA, B/D = 2.67, h/D = 3.0. \]
Figure 2 and 3 show non-dimensional hydrodynamic coefficients. From the figures one can see that significant changes occur when the wave angle reaches 75 degrees. One can observe that most of the hydrodynamic coefficients behave differently before and after \( L/B = 4 \).}

Figure 2 Non-dimensional vertical wave forces \( F^*_v = F_v/(0.5 \rho g A) \). \( B/D = 2.67, h/D = 3.0 \).

Figure 3 Non-dimensional wave exciting moments \( M'_r = M'_r/(0.5 \rho g h^2 A) \). \( B/D = 2.67, h/D = 3.0 \).

Figure 4 Non-dimensional sway added mass coefficients \( \mu_{21}' = \mu_{21}/(\rho BD) \). \( B/D = 2.67, h/D = 3.0 \).

Figure 5 Non-dimensional sway wave damping coefficients \( \lambda_{21}' = \lambda_{21}/(\rho BD (2gB)^{1/2}) \). \( B/D = 2.67, h/D = 3.0 \).

Figure 6 Non-dimensional heave added mass coefficients \( \mu_{22}' = \mu_{22}/(\rho BD) \). \( B/D = 2.67, h/D = 3.0 \).

Figure 7 Non-dimensional heave added mass coefficients \( \lambda_{22}' = \lambda_{22}/(\rho BD (2gB)^{1/2}) \). \( B/D = 2.67, h/D = 3.0 \).
Fig. 8 Non-dimensional roll added mass coefficients $\mu_{31} = \frac{\mu}{S_1 hD^3}$. $B/D = 2.67$, $h/D = 3.0$.

Fig. 9 Non-dimensional roll wave damping coefficients $\lambda_{31} = \frac{\lambda_{31}}{S_1 hD^3}$. $B/D = 2.67$, $h/D = 3.0$.

Fig. 10 Non-dimensional sway responses $X_1 = \xi_1 hA$. $B/D = 2.67$, $h/D = 3.0$.

Fig. 11 Non-dimensional heave responses $X_3 = \xi_3 hA$. $B/D = 2.67$, $h/D = 3.0$.

Fig. 12 Non-dimensional roll response $X_3 = \xi_3 hA$. $B/D = 2.67$, $h/D = 3.0$.

5. Summary

In order to understand the characteristics of floating breakwater in oblique waves, wave transmission coefficients, motion responses, and forces exerted on the breakwater are computed based on the linear potential theory with matching boundaries. Sway and heave wave exciting forces and roll moment acting on the floating breakwater are properly considered.
Fig. 13 Wave transmission coefficients based on Wave length/Breadth ratio L/B for various wave incident angles. ($\theta/D = 2.67, h/D = 3.0$)

Fig. 14 Wave transmission coefficients based on wave incident angle for Wave length/Breadth ratio L/B = 1 and 5. ($\theta/D = 2.67, h/D = 3.0$)

breakwater decrease as the incident wave angle increases. Hydrodynamic coefficients behave differently before and after a certain value of L/B as the incident wave angle changes. As the incident wave angle increases, all three motion responses decrease also. There exists a local minimum wave transmission coefficient which is a function of wave-length/breadth ratio. In short wave ranges, transmission coefficient increases as the incident wave angle increases. In long wave ranges, however, wave transmission coefficient decreases as the incident wave angle increases.

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References


