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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 reponses 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 has 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 deeper than 15-20m. Following McCartney[1982] if water depth is in excess of 6m, the floating breakwater is cost effective. Ginyer[1998] 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 $3,000/m, while the construction cost of the conventional fixed breakwater was estimated $7,500 - 10,000/m. Sugawara and Yoshimura [1984] reported an successful installation and operation of 270m long floating breakwater in Fukuyama 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 Gaithwaite [1988] for an 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 (Kinoshita and Saijo[1981], Morey et. al[1995], Mani[1991], Ohkuzu and Kashiwagi[1991], Nekato and Kokumai[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.

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

At the body boundary following conditions must be satisfied.

$$\nabla \Phi \cdot \vec{n} = \vec{V} \cdot \vec{n} \tag{2}$$

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.

Beside 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 Φ_I, the diffraction potential Φ_D, and the radiation potential Φ_R as follows.

$$\Phi = \Phi_I + \Phi_D + \Phi_R \tag{3}$$

Then on the body following condition must satisfy

$$\frac{\partial \Phi_I}{\partial n} + \frac{\partial \Phi_D}{\partial n} = 0, \qquad \frac{\partial \Phi_R}{\partial n} = \vec{V} \cdot \vec{n} \tag{4}$$

Let us consider a long cylinder parallel to y-axis. A monochromatic wave of frequency ω and wave number k approaches the floating breakwater with an angle θ. When θ is zero, it represents pure beam sea. We assume that the motion is small and time harmonic. Following Liu and Abbaspour[1982], one can write the velocity potential as follows using the uniformity in y-direction.

$$\Phi(x, y, z, t) = Re[\,\phi(x, z)\, e^{-i(\omega t - \beta y)}] \tag{5}$$

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

The complex velocity potential ϕ can be decomposed into three complex potentials.

$$\phi(x, z) = \phi_I + \phi_D + \phi_R \tag{6}$$

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

$$\phi_I = -\frac{igA}{\omega}\frac{\cosh k(z+h)}{\cosh kh}\, e^{i\alpha x} \tag{7}$$

$$\omega^2 = gk \tanh kh, \quad k^2 = \alpha^2 + \beta^2 \tag{8}$$

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

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

$$\nabla^2 \phi_D(x, z) - \beta^2 \phi_D = 0 \ \text{ in the fluid domain} \tag{9}$$

$$\frac{\partial \phi_D}{\partial z} - \omega^2 \frac{\phi_D}{g} = 0 \ \text{ on } z=0 \tag{10}$$

$$\frac{\partial \phi_D}{\partial n} = -\frac{\partial \phi_I}{\partial n} \ \text{ on the body} \tag{11}$$

$$\frac{\partial \phi_D}{\partial z} = 0 \qquad \text{on the bottom} \tag{12}$$

$$\lim_{\alpha x \to \pm\infty} \left(\frac{\partial}{\partial x} \mp i\alpha\right) \phi_D = 0 \tag{13}$$

The motion of the body can be expressed as follows.

$$x_j(t) = Re\{\xi_j e^{-i\omega t}\} \ \text{ for } j = 1, 2, 3 \tag{14}$$

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

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

$$\Phi_R = Re\{\xi_j \phi_j e^{-i\omega t}\}, \ \text{for } j=1,2,3 \tag{15}$$

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

$$\nabla^2 \phi_j(x, z) - \beta^2 \phi_j = 0 \ \text{ in the fluid domain} \tag{16}$$

$$\frac{\partial \phi_j}{\partial z} - \omega^2 \frac{\phi_j}{g} = 0 \ \text{ on } z=0 \tag{17}$$

$$\frac{\partial \phi_j}{\partial n} = -i\omega n_j, \ \text{for } j=1,2,3. \text{ on the body} \tag{18}$$

$$\frac{\partial \phi_j}{\partial z} = 0 \ \text{ on the bottom} \tag{19}$$

$$\lim_{\alpha x \to \pm\infty} \left(\frac{\partial}{\partial x} \mp i\alpha\right) \phi_j = 0 \tag{20}$$

where n_j is the extended normal vectors defined by following equation.

$$n_1 = n_x, \quad n_2 = n_z, \quad n_3 = x n_z - z n_x \tag{21}$$

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

$$F_i = i\omega\rho \int_S \phi_D(x, z)\, n_i\, ds \tag{22}$$

where ρ is the fluid density.

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

$$\mu_{ij} = -\frac{\rho}{\omega}\int_{S_o} Im[\phi_j]\, n_i\, ds \qquad \lambda_{ij} = \rho \int_{S_o} Re[\phi_j]\, n_i\, ds \tag{23}$$

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.

$$\sum_{j=1}^{3} [\,(B_{ij} + K_{ij}) - \omega^2(m_{ij} + \mu_{ij}) - i\omega\lambda_{ij}\,]\,\xi_i = f_i \tag{24}$$

where f_i is complex force, m_{ij} the mass matrix, μ_{ij} the added mass matrix, λ_{ij} the wave damping coefficient matrix, B_{ij} the hydrostatic stiffness matrix, K_{ij} the mooring stiffness matrix.

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

$$\Phi = Re\left\{\left(\phi_I + \phi_D + \sum_{j=1}^{3}\xi_j\phi_j\right)e^{-i(\omega t-\beta y)}\right\} \tag{25}$$

Then the free surface profile can be calculated as

$$\eta(x,t) = -\frac{1}{g}\frac{\partial\Phi}{\partial t}\Bigg|_{z=0} \tag{26}$$

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

$$C_T = \frac{A_o^+}{A} \tag{27}$$

where A_o^+ 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 Helmoltz equation is given by

$$G = -K_o(\beta r) \tag{28}$$

$$r = \sqrt{(x-x_i)^2 + (z-z_i)^2}$$

where K_o 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_i, z_i). Using the Green's second identity and the fundamental solution, we can obtain the following integral equation.

$$\begin{pmatrix} 2\pi \\ \sigma_i \end{pmatrix}\phi_i = \int_\Gamma \left(\phi\frac{\partial G}{\partial n} - G\frac{\partial\phi}{\partial n}\right)d\Gamma \tag{29}$$

where 2π is used for internal points and σ_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

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

$$+\begin{pmatrix} 0 \\ \phi_I \end{pmatrix} \begin{matrix} x > x^+ \\ x < x^- \end{matrix} \tag{30}$$

where

$$\omega^2 = gk\tanh kh \tag{31}$$

$$\omega^2 = gk_n\tan k_n h$$

$$W_0^\pm = e^{\pm i\alpha x}\frac{\cosh k(z+h)}{\cosh kh} \tag{32}$$

$$W_m^\pm = e^{\pm i\alpha x}\frac{\cos k_m(z+h)}{\cos k_m h}.$$

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

At the matching boundary we impose following conditions.

$$\phi = \phi^\pm,\ \frac{\partial\phi}{\partial n} = \pm\frac{\partial\phi^\pm}{\partial x} \text{ at } x = x^\pm \tag{33}$$

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 (θ=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 θ. When θ 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 θ increases.

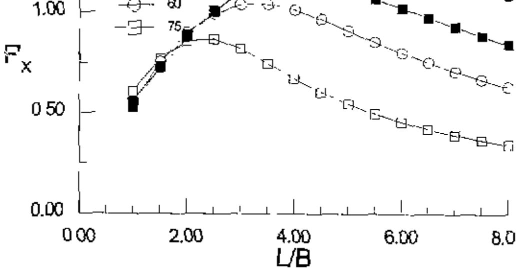

Fig. 1 Non-dimensional horizontal wave forces $F'_x=F_x/(0.5\rho gBA)$. B/D = 2.67, h/D = 3.0.

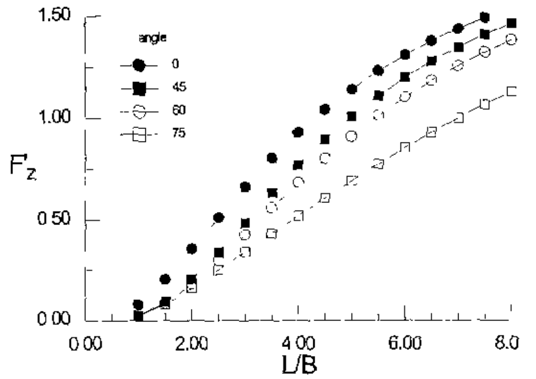

Fig. 2 Non-dimensional vertical wave forces $F'_z=F_z/(0.5\rho gBA)$. B/D = 2.67, h/D = 3.0.

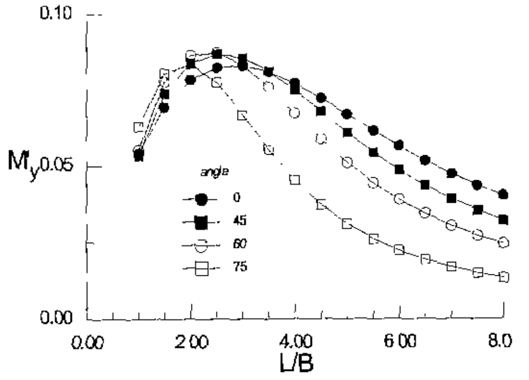

Fig. 3 Non-dimensional wave exciting moments $M'_y = M'_y/(0.5\rho gB^2A)$. B/D = 2.67, h/D = 3.0.

Figure 2 and 3 for the vertical wave forces and the roll moment. In this figure we can also see that the vertical wave force acting on the floating breakwater decreases as θ increases. We can see similar tendency for the roll moment.

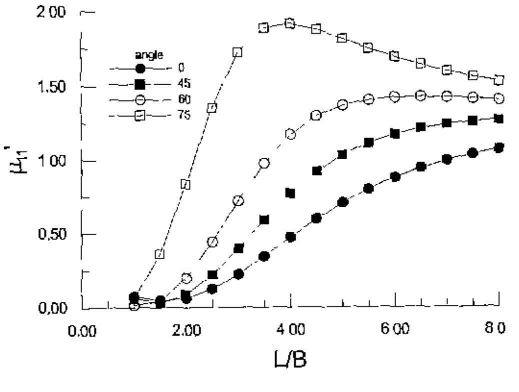

Fig. 4 Non-dimensional sway added mass coefficients $\mu_{11}' = \mu_{11}/(\rho BD)$. B/D = 2.67, h/D = 3.0.

Figures 4 - 9 show non-dimensional hydro- dynamic 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.

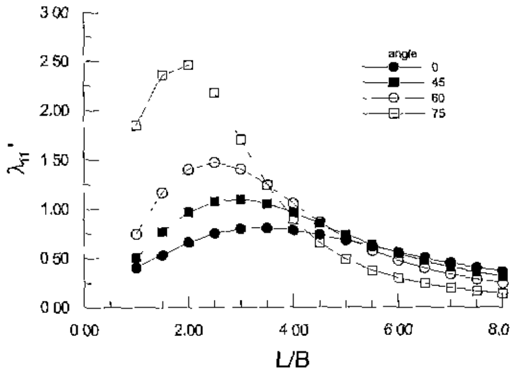

Fig. 5 Non-dimensional sway wave damping coefficients $\lambda_{11}' = \lambda_{11}/\rho D(2gB)^{1/2}$. B/D = 2.67, h/D = 3.0.

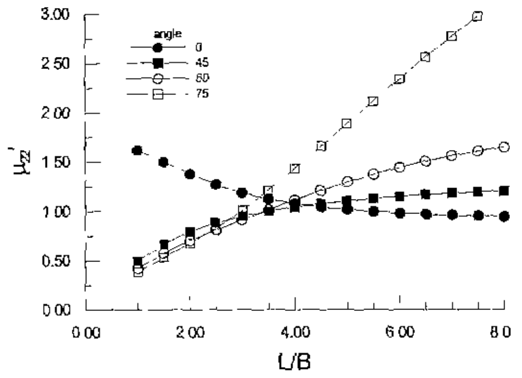

Fig. 6 Non-dimensional heave added mass coefficients $\mu_{22}' = \mu_{22}/(\rho BD)$. B/D = 2.67, h/D = 3.0.

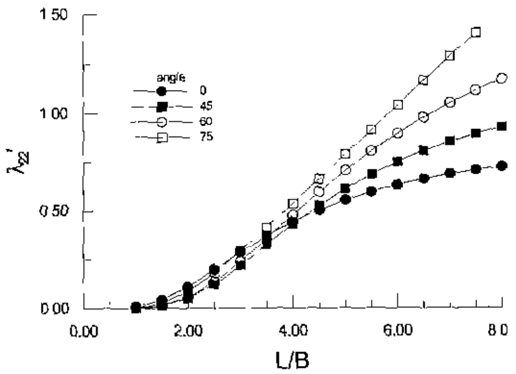

Fig. 7 Non-dimensional heave added mass coefficients $\lambda_{22}' = \lambda_{22}/\rho D(2gB)^{1/2}$. B/D = 2.67, h/D = 3.0.

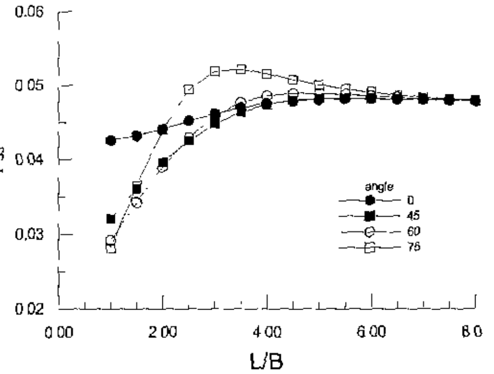

Fig. 8 Non-dimensional roll added mass coefficients $\mu_{33}' = \mu_{33}/(\rho B^2 D)$. B/D = 2.67, h/D = 3.0.

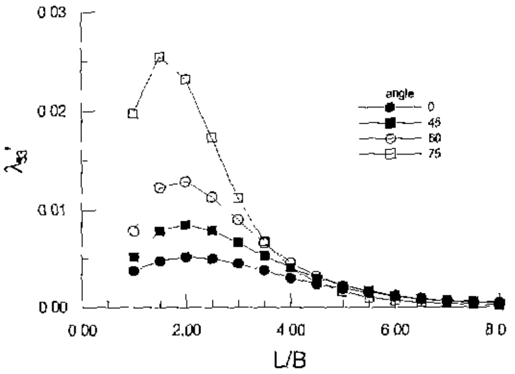

Fig. 9 Non-dimensional roll wave damping coefficients $\lambda_{33}' = \lambda_{33}/\rho BD(2gB)^{1/2}$. B/D = 2.67, h/D = 3.0

Figures 10, 11 and 12 show non- dimensional motion responses of sway x'_1, heave x'_2 and roll x'_3. As the incident wave angle increases, all three motion reponses decrease. In figure 17 ordinate scale of 1.0 corresponds to roll angles of 9 degrees approximately when the wave steepness ε $(=H/L)$ is 0.05.

Figure 13 shows wave transmission coefficient C_T at various incident wave angles. There exist local minimum values near L/B=3.5. Wave transmission coefficient shows different characteristics before and after the local minimum point of C_T. Before the minimum point of C_T (i.e. short wave ranges) wave transmission coefficient increases as the angle θ increases. In long wave ranges, however, C_T decreases as θ increases. Figure 14 clearly shows the behavior of C_T for various θ with two different L/B ratio at 1.0 and 5.0.

In most of the floating breakwater design process, long waves rather than short ones cause more concern. In this paper it is found that the wave transmission coefficient decreases as the wave incident angle increases in long wave ranges. Therefore two dimensional characteristics of the floating breakwater can be used as a good asset of the performance of the floating breakwater, provided that the wave diffraction around the floating breakwater is properly considered.

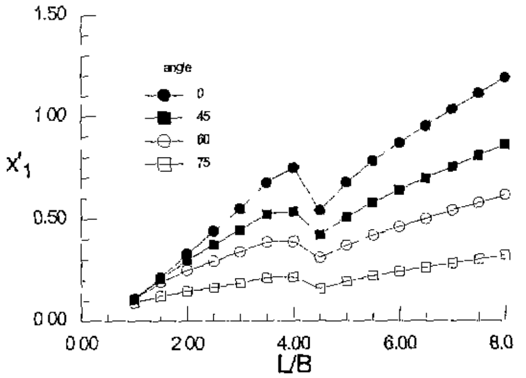

Fig. 10 Non-dimensional sway responses $x_1' = |\xi_1|/A$. B/D = 2.67, h/D = 3.0.

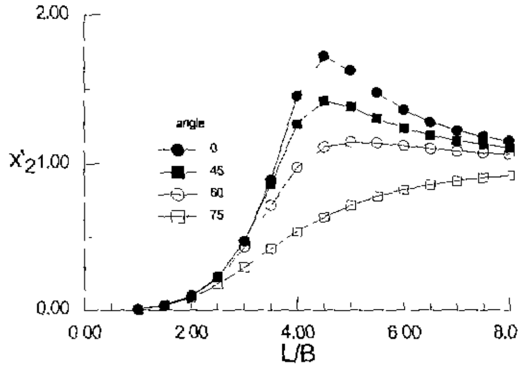

Fig. 11 Non-dimensional heave responses $x_2' = |\xi_2|/A$. B/D = 2.67, h/D = 3.0.

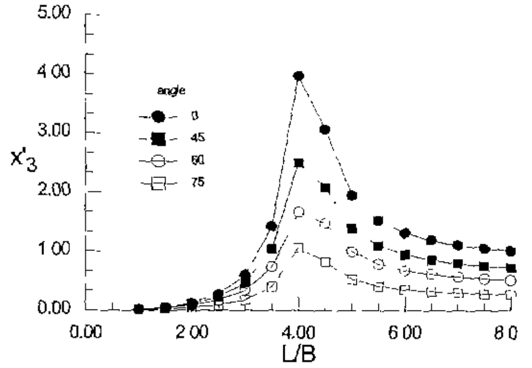

Fig. 12 Non-dimensional roll response $x_3' = |\xi_3|/(kA)$ B/D = 2.67, h/D = 3.0.

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

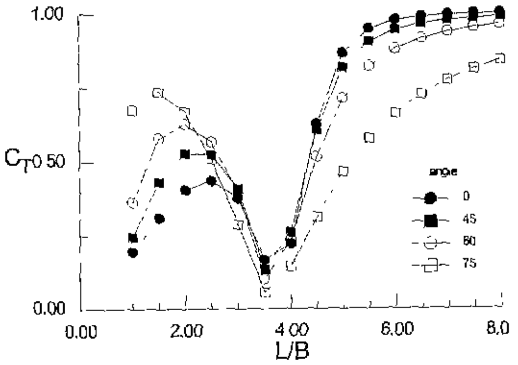

Fig. 13 Wave transmission coefficients based on Wave length/Breadth ratio *L/B* for various wave incident angles. (*B/D* = 2.67, *h/D* = 3.0)

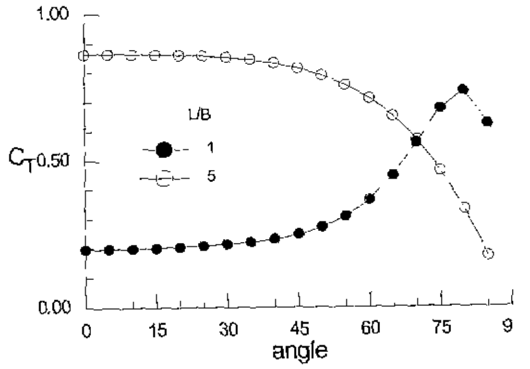

Fig. 14 Wave transmission coefficients based on wave incident angle for Wave length/Breadth ratio *L/B*= 1 and, 5. (*B/D* = 2.67, *h/D* = 3.0)

breakwater decrease as the incident wave angle increases. Hydrodyamic 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 reponses 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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