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NUMERICAL ANALYSIS OF IRREGULAR-SHAPED FLOATING BREAKWATER

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Abstract
It is known that the floating type of breakwater is more preferable than conventional or fixed-type one especially by considering its economical and technical benefits. However, the common shape of a floating breakwater, which is usually simply a rectangular shape, could only attenuate waves in a limited range of frequency especially in short wavelength region. In longer wavelength region, it will just move following the seawater motions as a small object. In order to address this problem, an irregular-shaped floating breakwater, which utilizes the relative motion of water inside its body, which as a result could attenuate incoming waves in relatively longer wavelength region, needs to be implemented. By analyzing the relation of hydro dynamical and geometrical influences to the performance, the optimal shape and dimension can be obtained. The performance of the models described by performance index (PI) for clear and convenient comparison and assessment. The analysis and numerical computations based on the potential flow theory.

Keywords
Potential flow, boundary element method, irregular-shaped floating breakwater, shape optimization, performance index.

INTRODUCTION

One common choice to protect the near-shore area is fixed type breakwater ranging from simple structures such as rubble mound breakwater to more complicated structures such as caisson breakwater. However, the construction cost and technical or engineering problems of this type breakwater especially when dealing with relatively deep sea condition urge people to think a better device for the purpose.

Therefore, by considering the economical and technical factors as well as other benefits such as fresh water preservation, design flexibility, etc., the floating type breakwater has become interesting and more preferable to be used than fixed type one. As a result, the practical demand of floating breakwater is growing and consequently makes many researchers get interested to perform research about it.

However, the past research have shown that conventional type floating breakwaters which are usually simply of rectangular shape, could only attenuate waves in a limited range of frequency especially in short wavelength. It is almost impossible to obtain a good performance in longer wavelength by just modifying the dimension of this rectangular-shaped model because it will just move following the seawater motions as a small object in the long wavelength region.

In order to address the problem, instead of modifying the dimension, the shape of the model should be modified so that the seawater can interact inside the body, which can change the phase of body motions and consequently can reduce the amplitude of incoming wave. We refer to this kind of model as irregular-shaped floating breakwater.

Moreover, the advent of numerical computation such as Boundary Element Method (BEM) which has its accuracy been confirmed by experiment, create a convenient way to analyze and predict the performance of any shapes including irregular-shaped floating breakwaters. The computation results can help and guide us to design an optimal floating breakwater without spending high cost for constructing unreliable real model. Another advantage from the numerical analysis and computation is the flexibility to calculate and analyze arbitrary shape models in relatively short time period.

Using BEM, this study will analyze the hydro dynamical and geometrical influences of irregular-shaped floating breakwater models to the performance, which indicated by the transmitted wave amplitude and in some cases by the body motion amplitudes. In analysis, a series of numerical confirmation will be done to confirm the accuracy of computed results.

However, the analysis and computation will be restricted to only 2D (two-dimensional) problem. Moreover, the study also only analyzes the case when all 2D body motions are free. From the analysis, the performance will be described and represented using performance index (PI) so that it will be easier to evaluate and assess the performance of the model. The final objective is to obtain a model, which has high and optimal performance.

Definition of Problem

Assuming the fluid to be incompressible and inviscid with irrotational motion, the velocity potential is introduced and the flow around a 2-D floating body in regular incident waves is considered. The wave-induced motions of a body and associated fluid motion are assumed to be linear in the incident-wave amplitude and harmonic in time with circular frequency ω of the incident wave. In what follows, all oscillatory quantities will be expressed in complex form, with the time dependence $e^{i\omega t}$ understood.

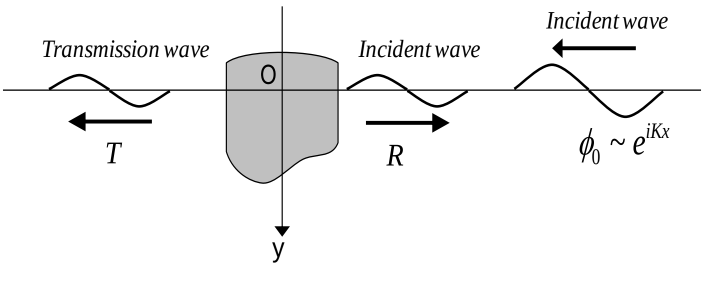


Figure 1.
Reflection and transmission waves for an incident wave incoming from the positive *x*-axis.

In order to treat the problem in general, an asymmetric body is considered; in this case, depending on the incoming direction of incident wave, the flow field around the body may be different. Accordingly, as shown in Fig. 1, the case to consider is when the incident wave is incoming from the positive x-axis and write the resulting velocity potential in the form

$$\phi(x,y) = \frac{g\zeta_a}{i\omega}\{\phi_D(x,y) - KX_j\phi_j(x,y)\} \equiv \frac{g\zeta_a}{i\omega}\varphi(x,y) \tag{1}$$

$$\phi_D = \phi_0 + \phi_4, \phi_0 = e^{-Ky+iKx}, K = \frac{\omega^2}{g} \tag{2}$$

where ζ_a is the amplitude of incident wave and g is the acceleration of gravity. ϕ_D is the diffraction potential which is the sum of the incident-wave potential ϕ_0 and the scattering potential ϕ_4. The water depth is assumed to be infinite and the wave number K of a progressive wave satisfies the dispersion relation given by (2). X_j denotes the complex amplitude of the body motion in the j-th mode (j = 1 for sway, j = 2 for heave, and j = 3 for roll), and ϕ_j is the radiation potential with unit velocity in the j-th direction. The summation sign with respect to j is deleted throughout the paper with the convention that any term of an equation containing the same index twice should be summed over that index.

The asymptotic expression of the normalized velocity potential at $x \to \pm\infty$ can be given as

$$\begin{aligned}\varphi(x,y) &= \phi_D(x,y) - KX_j\phi_j(x,y) \\ &\sim e^{-Ky}\left[e^{ikx} + iH_4^{\pm}e^{\mp iKx} - KX_j iH_j^{\pm}e^{\mp iKx}\right]\end{aligned} \tag{3}$$

Here the upper lower sign in the double sign is taken according to whether $x \to +\infty$ or $-\infty$, respectively. $H_4^{\pm}$ and $H_j^{\pm}$ $(j = 1\sim3)$ denote the Kochin functions associated with the far-field scattered and radiated waves, respectively. From (3), the velocity potential on the free surface $(y = 0)$ may be expressed as

$$\varphi(x,0) \sim \begin{cases} e^{iKx} + R_F e^{-iKx} & \text{as } x \to +\infty \\ T_F e^{iKx} & \text{as } x \to -\infty \end{cases} \tag{4}$$

where

$$\left.\begin{aligned} R_F &= R_D - iKX_jH_j^{+}, \quad R_D = iH_4^{+} \\ T_F &= T_D - iKX_jH_j^{-}, \quad T_D = 1 + iH_4^{-} \end{aligned}\right\} \tag{5}$$

R and T are defined as the coefficients of reflection and transmission waves, respectively. Suffix D to these coefficients indicates the quantities for the diffraction problem; likewise suffix F indicates the quantities for the case where a body is freely oscillating in an incident wave which is the case considered in the present study.

Numerical Solution Method

The diffraction ($\psi_j = \phi_D$) and radiation ($\psi_j = \phi_j$) potentials are determined directly by solving an integral equation for the velocity potential ψ_j, expressed in the form

$$C(P)\psi_j(P) + \int_{S_H} \psi_j(Q)\frac{\partial}{\partial n_Q}G(P;Q)dl(Q)$$

$$= \begin{cases} \phi_0(P) & (j = D) \\ \int_{S_H} n_j(Q)G(P;Q)dl(Q) & (j = 1\sim 3) \end{cases} \tag{6}$$

Here S_H denotes the body surface below $y = 0$, on which the body boundary conditions

$$\frac{\partial \phi_D}{\partial n} = 0, \qquad \frac{\partial \phi_j}{\partial n} = n_j \tag{7}$$

are satisfied, where n_j denotes the j-th component ($n_1 = n_x$, $n_2 = n_y$, and $n_3 = xn_2 - yn_1$) of the normal vector, which is defined as positive outward from the body surface. $P = (x, y)$ and $Q = (\xi, \eta)$ denote the field and integration points, respectively, located on the body surface and $C(P)$ denotes the solid angle. $G(P;Q)$ represents the free-surface Green function in water of infinite depth. Its exact expression written as

$$G(P;Q) = \frac{1}{2\pi}\log\frac{r}{r_1} - \frac{1}{\pi}\lim_{\mu\to 0}\int_0^\infty \frac{e^{-ky}\cos kx}{k-(K-i\mu)}dk$$

$$= \frac{1}{2\pi}\log\frac{r}{r_1} - \frac{1}{\pi}\mathrm{Re}[e^{-KZ}E_1(-KZ)] + ie^{-KZ} \tag{8}$$

where

$$\left.\begin{matrix} r \\ r_1 \end{matrix}\right\} = \sqrt{(x-\xi)^2 + (y \mp \eta)^2}, \;\; Z = (y+\eta) + i|z-\xi|$$

E_1 = Exponential integral function with complex variable

Substituting (8) into (6) with $C(P)$ = 1 for the solid angle, the asymptotic form of the velocity potential at $x \to \pm\infty$ can be readily obtained. Since the results are expressed as (4), the Kochin functions in the diffraction and radiation problem can be defined explicitly as follows

$$H_j^{\pm}(K) = \int_{S_H}\left(\frac{\partial \phi_j}{\partial n} - \phi_j\frac{\partial}{\partial n}\right)e^{-K\eta \pm iK\xi}ds \quad (j = 1\sim 3) \tag{9}$$

$$H_4^{\pm}(K) = -\int_{S_H} \phi_D \frac{\partial}{\partial n} e^{-K\eta \pm iK\xi} ds \tag{10}$$

The integral equation (6) is solved by the so-called constant panel collocation method; that is, the body surface of $y = 0$ is divided into N segments and on each segment the unknown velocity potential is assumed to be constant. Then, considering N different points for $P(x, y)$, (6) can be recast in a linear system of simultaneous equations for N unknowns. By solving these simultaneous equations, the velocity potentials on the body surface can be obtained.

Once the velocity potentials on the body surface are determined, it is straightforward to compute the hydrodynamic forces. With the convention that all quantities are written in nondimensional form, the hydrodynamic forces in the diffraction and radiation problems are expressed in the form

$$\left.\begin{aligned} E_j &= \int_{S_H} \phi_D n_j dl, \\ f_{jk} &= -\int_{S_H} \phi_k n_j dl = A_{jk} - iB_{jk} \end{aligned}\right\} \tag{11}$$

where E_j is the wave-exciting force in the j-th direction, and A_{jk} and B_{jk} are the added-mass and damping coefficients, respectively, in the j-th direction due to the k-th mode of motion. In terms of these forces, the equations of body motion with respect to the origin of the coordinate system can be expressed in a matrix form as

$$\left[-K\left(M_{jk} + f_{jk}\right) + C_{jk}\right] X_k = E_j \tag{12}$$

For $j = 1 \sim 3$, where M_{jk} denotes the mass matrix and its nonzero values are in the diagonal ($j = k$), which are the body mass *(m)* for $j = 1$ and 2 and the moment of inertia for $j = 3$, and also $M_{13} = M_{31} = -my_G$ and $M_{23} = M_{32} = mx_G$ for off-diagonals, where (x_G, y_G) is the position of the center of gravity, generally unequal to the origin of the coordinate system due to asymmetry of a body. C_{jk} denotes the restoring force coefficients due to the static pressure. It should be noted that both M_{jk} and C_{jk} are real quantities and the symmetry relation of $M_{jk} = M_{kj}$ and $C_{jk} = C_{kj}$ holds as is the same for the added-mass and damping coefficients.

After solving (12), we can compute the reflection and transmission waves using (5). These coefficients and the amplitude of wave-induced motions of a body are nondimensionalized using the incident-wave amplitude.

Performance Assessment

The main objective of the study is to design a floating breakwater model which has a high performance. The performance is indicated by a low transmission coefficient and in some cases also low body motion amplitudes. Conventional method of evaluating low transmission coefficient or motion amplitude is by analyzing and comparing the results plotted in a graph. This method is inconvenient to be used when the results have only small difference or the general tendency is different, which consequently could lead us to wrong conclusions.

In order to avoid that situation, it is essential to transform the results before evaluating and comparing them. This study will transform the result into an assessment tool which is called Performance Index (PI). Performance Index (PI) represents the magnitude of an assessment item for performance evaluation. The PI has range from 0 to infinity where the larger PI, the poorer performance. They are obtained by integrating the item performance curve along a certain maximum value as illustrated in Fig. 2.

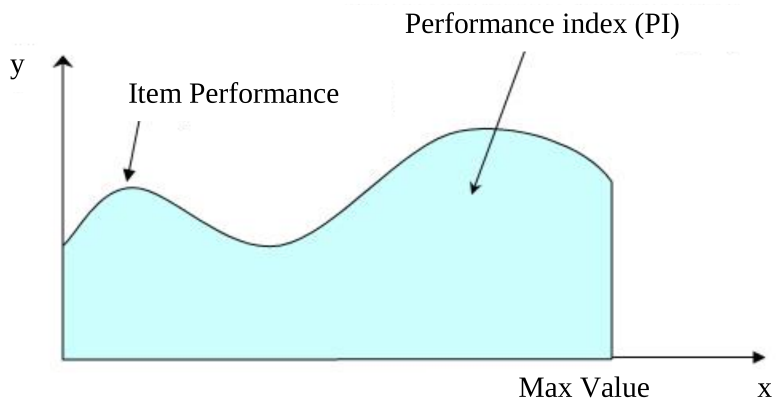


Figure 2.
Performance index (PI) definition.

The area under the curve which is already called Performance Index will have range which depends on the value of variable in *x*- and *y*-axis. As a result, each PI will have different range which makes us unable to compare them. Therefore, the PI needs to be nondimensionalized by the following formula

$$d' = \frac{d}{\sqrt{d^2 + a}} \qquad (13)$$

where *d'* is the nondimensionalized value, *d* is the original value or in this case is PI which has only positive value, and *a* is a positive non-zero value. The value of *a* will determine the difference between *d'* and *d*. Setting higher value of *a* will make the graph between *d* and *d'* smoother as shown in Fig. 3. The value of smoothing parameter *a* depends on how smooth we want to set *d*-*d'* and how large the value of *d* is.

In this study, the performance of floating breakwater is evaluated from two indicators which are the transmission coefficient and the body motion amplitudes of sway, heave, and roll. However, a floating breakwater which has low transmission coefficient is much more preferable than the one which has low motion amplitude.

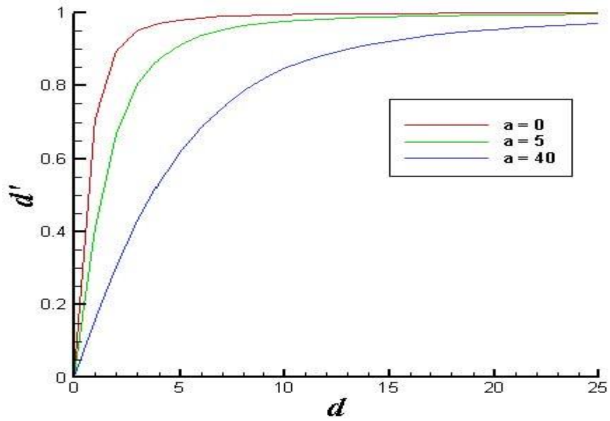


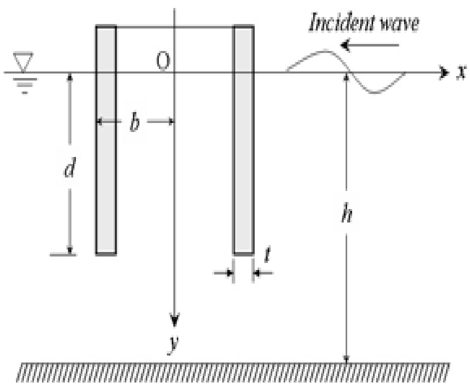
Figure 3.
Relation of *d'* and *a*.

Results Analysis

As explained previously, all quantities will be in nondimensional form by using the body breadth $B=2b$ as a representative length for nondimensionalization.

Model Configuration

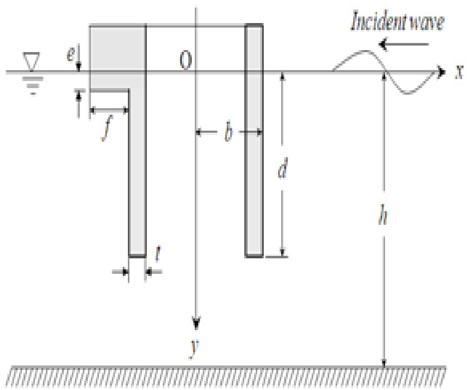
In order to clearly understand the influence of each component of a more complicated model, the basic model which is called Model-1 is chosen to be a simple symmetric model with only a rectangular shape extending downward on both sides as shown in Fig. 4. The dimensions used in computation for Model-1 are shown in a table next to the figure.



Notation	Length
b	1
d	1.25
t	0.15
h	5

Figure 4.
Model-1 coordinate system and dimension.

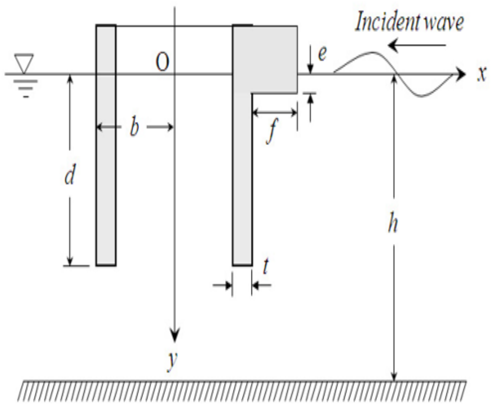
The study conducted by Kashiwagi et al. [4] shows that a horizontal fin could make the transmission coefficient small. This study was continued by Kashiwagi and Takashima [3] which shows that the placement of the horizontal fin in the free surface could give rise to more zero transmission frequency in a certain wavelength region. Even though the case might be different, but using the same principle, we could expect performance improvement by placing this horizontal fin. Thus, in Model-1, a horizontal fin is attached on the left side of the body just below the free surface which is called Model-2 as shown in Fig. 5.



Notation	Length
b	1
d	1.25
t	0.15
e	0.15
f	0.5
h	5

Figure 5.
Model-2 coordinate system and dimension.

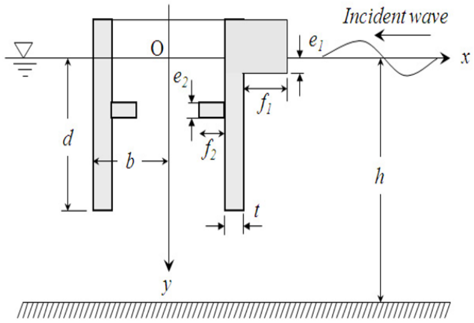
Furthermore, from the same study by Kashiwagi et al. [4], it is known that an asymmetric body will have exactly the same transmission coefficient. However, because the motion amplitude is different, then it is important to compare the amplitude when the fin is attached on the right side of the body which is called Model-3 in the present study as shown in Fig. 6. The dimensions used in computation are also shown in a table next to the figure.



Notation	Length
b	1
d	1.25
t	0.15
e	0.15
f	0.5
h	5

Figure 6.
Model-3 coordinate system and dimension.

Furthermore, the main advantage of irregular-shaped floating breakwater is that the relative motion of water inside the body may be able to change the phase of body motion. Therefore, it will be also beneficial to place a horizontal fin inside the body of the model which can be used to alter or adjust the flow field and interaction of water inside the body. The model which has a horizontal fin on both sides inside the body will be called Model-4. This model shape and dimensions are shown in Fig. 7.



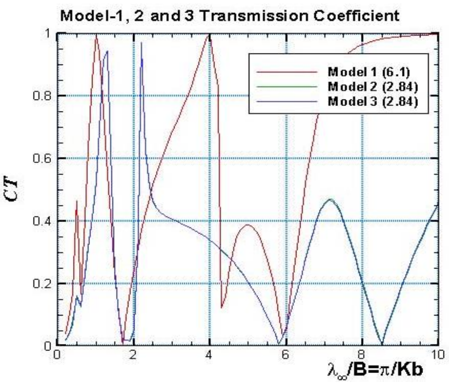
Notation	Length
b	1
d	1.25
t	0.05
e_1	0.05
f_1	0.5
e_2	0.05
f_2	0.15
h	5

Figure 7.
Model-4 coordinate system and dimension.

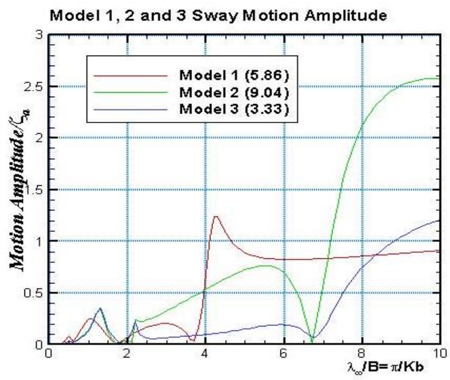
For the value of metacentric height *GM* used in computing for each model is assumed to be 2.0.

Computation Results and Discussion

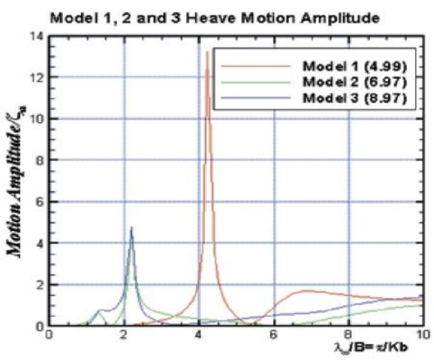
Based on the configured models above, the computations are performed and the results of computations for the transmission coefficient and motion amplitude for Model-1 to 3 are shown in Fig. 8. The number in parenthesis in each legend of the graph indicates the PI of corresponding lines.



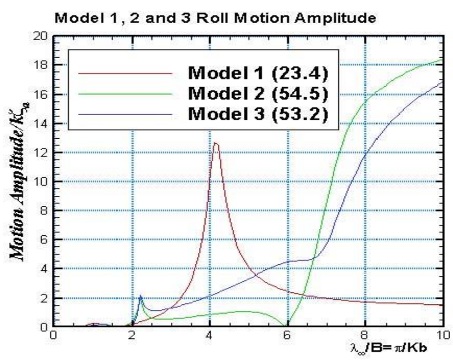
(a)



(b)



(c)



(d)

Figure 8.
Transmission coefficients and motion amplitudes of model-1, 2, 3.

From Fig. 8, we can see that the transmission coefficient of Model-1 is poor as can be seen from the graph or their PI for more accurate assessment. Then, by attaching a horizontal fin as in Model-2 and 3, the performance in terms of the transmission coefficient can be improved especially in longer wavelength. The improvement is mainly caused by the existence of zero transmission frequency in the longer wavelength region $\lambda_\infty/B>6$.

Another thing that we can notice in this figure is that attaching the horizontal fin in the left side (Model-2) or the right side (Model-3) will have exactly the same transmission coefficient, which was also one of the conclusions of the study by Kashiwagi [1]. Moreover, we can also see that performance of Model-3 is relatively better than Model-2 by considering the large difference in sway motion amplitude shown in Fig. 8(b). This consideration is the reason to choose keeping the right horizontal fin in the next model.

Therefore, in order to compare and see the improvement clearly which appears in Model-4, the computation result of Model-4 will be plotted together with the computation results of Model-3 as shown in Fig. 9.

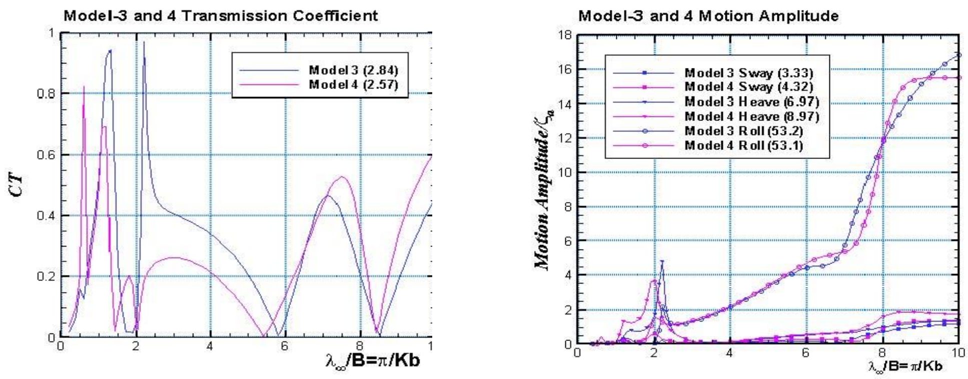


Figure 9.
Transmission coefficients and motion amplitudes of model-3 and 4.

The computation results in Fig. 9 indicate clear improvement which is achieved by attaching a horizontal fin in each side of inside body or Model-4. Even though the motion amplitude seems not to be significantly influenced, we still can say that Model-4 is the best model compared to other models because the transmission coefficient is much more important than the motion amplitude.

CONCLUSIONS

- A horizontal fin on the right side of the body (i.e. weather side) can improved the performance in the longer wavelength region.
- The 'reverse' property has been proven to be held true also for irregular-shaped floating breakwater models.
- Attaching a horizontal fin on the right side of the body (i.e. weather side) gives better motion amplitude performance than attaching on the left side.
- The model with horizontal fin attached inside of the body and on right side of the outside (Model-4) has the optimal performance.

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