Time-domain hydrodynamic analysis of pontoon-plate floating breakwater

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Abstract: The hydrodynamic behaviors of a floating breakwater consisting of a rectangular pontoon and horizontal plates are studied theoretically. The fluid motion is idealized as two-dimensional linear potential flow. The motions of the floating breakwater are assumed to be two-dimensional in sway, heave, and roll. The solution to the fluid motion is derived by transforming the governing differential equation into the integral equation on the boundary in time domain with the Green’s function method. The motion equations of the floating breakwater are established and solved with the fourth-order Runge-Kutta method to obtain the displacement and velocity of the breakwater. The mooring forces are computed with the static method. The computational results of the wave transmission coefficient, the motion responses, and the mooring forces of the pontoon-plate floating breakwater are given. It is indicated that the relative width of the pontoon is an important factor influencing the wave transmission coefficient of the floating breakwater. The transmission coefficient decreases obviously as the relative width of the pontoon increases. The horizontal plates help to reduce the wave transmission over the floating breakwater. The motion responses and the mooring forces of the pontoon-plate floating breakwater are less than those of the pontoon floating breakwater. The mooring force at the offshore side is larger than that at the onshore side.

Key words: hydrodynamic analysis; pontoon-plate floating breakwater; transmission coefficient; motion response; mooring force

1 Introduction

Floating breakwaters can offer an alternative to conventional bottom-founded breakwaters in some coastal and offshore areas. Compared with the conventional fixed breakwaters, floating...
breakwaters are easier to build in the case of deep water areas, and have strong seawater exchanging ability to prevent the coastal area from being contaminated. Furthermore, floating breakwaters have advantages of lower investment, good applicability in the poor foundations, good flexibility and mobility, quick installation, and easy retrieval. In recent years, floating breakwaters are paid more and more attention. Various types of configurations for the floating breakwaters have been proposed and studied by many investigators.

McCartney (1985) introduced four types of floating breakwaters, including the box pontoon, mat, and tethered types. Drimer et al. (1992) presented a simplified approach for a floating breakwater where the breakwater width and incident wavelength are taken to be much larger than the gap between the breakwater and seabed. Xing and Zhang (1996) presented a type of floating breakwater which combined the surface wave-absorbing structure with a damper structure underneath, and it was proved that the transmissivity lowered to 50%-60% in the long wave transfer condition. Williams and Abul-azm (1997) investigated the hydrodynamic properties of a dual pontoon floating breakwater consisting of a pair of rectangular sectional floating cylinders connected by a rigid deck. Sannasiraj et al. (1998) conducted an experimental and theoretical investigation of the behavior of pontoon-type floating breakwaters, and studied the motion responses, the mooring forces, and the wave attenuation characteristics. Bayram (2000) conducted an experimental study of an inclined pontoon breakwater in intermediate water depths for use with small commercial vessels and yacht marinas. Matsunaga et al. (2002) presented a new type of steel floating breakwater with truss structure and investigated its performance in wave absorption. Ikesue et al. (2002) proposed a floating breakwater with two boxes for deep-water areas, and studied the performance characteristics. Liang et al. (2004) proposed a spar buoy floating breakwater, and studied the wave reflection and transmission characteristics and the wave-induced tension of the mooring lines. Gesraha (2006) carried out a numerical investigation of the performance of a \( \pi \)-shaped rectangular floating breakwater. Mizutani and Rahman (2006) investigated experimentally the performance of a rectangular-shaped floating breakwater with three different types of mooring systems. Dong et al. (2008) conducted two-dimensional physical model tests to measure the wave transmission coefficients of three types of floating breakwaters with a single box, double boxes, and board nets, respectively, under regular waves with or without currents. Diamantoulaki et al. (2008) investigated numerically the performance of flexible pile-restrained floating breakwaters under the action of incident waves in the frequency domain. Dong et al. (2009) conducted an experimental investigation of the hydrodynamic characteristics of a box-type floating breakwater and studied the effects of the relative width of the floating body and relative drag length coefficient of the mooring chain on the motion responses and mooring forces. Wang et al. (2009) proposed a new kind of floating breakwater, the vertical pile-restrained pontoon-plate floating breakwater, and studied experimentally the hydrodynamic behaviors of this structure. Koo (2009) studied the wave
blocking performance of a motion-constraint pneumatic floating breakwater in time domain using the fully nonlinear numerical wave tank (NWT) technique. Liu et al. (2009) carried out a numerical investigation on the hydrodynamic performance of a submerged breakwater with two layers of horizontal plates. They examined the effects of the submerged depth, thickness, and space of plates on the reflection and transmission coefficients of the breakwater. Wang and Sun (2010) presented a novel configuration of the floating breakwater that was fabricated with large numbers of diamond-shaped blocks in an experiment and studied its performance under wave actions. Diamantoulaki and Angelides (2010, 2011) investigated the overall performances of a non-moored array of floating breakwaters and a cable-moored array of floating breakwaters connected by hinges under the action of monochromatic linear waves in the frequency domain.

Despite those theoretical and experimental researches done in the past years, due to the unsatisfactory wave dissipating effect of the floating breakwater on long waves in engineering, the floating breakwater remains a topic of studies. In this paper, the performance of floating breakwaters consisting of a rectangular pontoon and horizontal plates is numerically investigated. A two-dimensional, linear, and theoretical model in time domain is developed based on the boundary element method. The motion equations of the floating breakwater are established to obtain the motion displacement and velocity. The mooring forces are computed with the static method. The numerical results of the wave transmission coefficient, the motion responses, and the mooring forces of the floating breakwater are presented.

2 Mathematical model

The mathematical model is developed based on the linear potential theory in time domain to solve the wave diffraction and radiation problem of the floating breakwater. The fluid is assumed inviscid and incompressible, and the flow irrotational and periodic. The sketch of the computational model of the pontoon-plate floating breakwater is shown in Fig. 1.

![Fig. 1 Sketch of computational model of pontoon-plate floating breakwater](image)

In Fig. 1, the Cartesian coordinate system \(xOz\) is employed. The origin is at the undisturbed water surface. The \(x\)-axis is directed to the right, and the \(z\) coordinate is measured positive upwards. \(W, H,\) and \(D\) are the width, height, and draft of the pontoon, respectively; \(W_p\)
and \( t_p \) are the width and thickness of the plate, respectively; \( e \) is the space between two plates; \( r_0 \) is the distance between the origin of the coordinate system and the starting location of the artificial beach; \( h \) is the water depth; \( \gamma \) is the inclination angle of chains at the mooring point; and \( \beta L \) is the width of the damping area, where \( L \) is the characteristic wave length, and \( \beta \) is a relevant coefficient.

### 2.1 Governing equations

For waves at a finite water depth, the wave steepness is usually small. The waves can be considered linear or weakly nonlinear ones. For the case of the interaction between the structure and linear waves or weakly nonlinear waves, the responses of the structure are generally not large, which can be considered finite amplitude motions. Therefore, the governing equation for the velocity potential can be established at the mean water surface and mean body surface, and solved linearly.

With the linearity assumption, the total velocity potential \( \phi \) is taken as the sum of the incident wave potential \( \phi_i \) and scattered potential \( \phi_s \):

\[
\phi = \phi_i + \phi_s
\]

where \( \phi_i \) at the finite water depth is defined as

\[
\phi_i = \frac{gA}{\omega} \frac{\cosh(k(z + h))}{\cosh(kh)} \sin(kx - \omega t)
\]

where \( A \) is the wave amplitude, \( g \) is the gravitational acceleration, \( k \) is the wave number, \( t \) is time, and \( \omega \) is the frequency of the incident wave.

In the fluid domain, the velocity potential \( \phi \) satisfies the Laplace equation:

\[
\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0
\]

The scattered potential \( \phi_s \) satisfies the linearized kinematic and dynamic conditions at the free water surface, shown as follows:

\[
\frac{\partial \phi_s}{\partial z} - \frac{\partial \eta_s}{\partial t} = 0
\]

\[
\frac{\partial \phi_s}{\partial t} + g \eta_s = 0
\]

where \( \eta_s \) is the water surface elevation. The linearized body surface boundary condition is given by

\[
\frac{\partial \phi_s}{\partial n} - V_n \frac{\partial \phi_i}{\partial n} = 0
\]

where \( n \) is the unit normal vector pointing outwards from the body surface, and \( V_n \) is the normal velocity at the body surface.

The boundary condition at the sea bottom is written as

\[
\frac{\partial \phi_s}{\partial n} = 0
\]
Besides, the far-field boundary condition is required to assure that the scattered waves propagate forwards. Commonly, the artificial beach is introduced at the free water surface to absorb the waves. In this study, the damping terms are added to the kinematic and dynamic conditions as follows:

\[
\begin{align*}
\frac{\partial \eta_s}{\partial t} &= \frac{\partial \phi_s}{\partial z} - v(r) \eta_s \\
\frac{\partial \phi_s}{\partial t} &= -g \eta_s - v(r) \phi_s
\end{align*}
\]  

(8)

(9)

where

\[v(r) = \begin{cases} 
\alpha \omega \left( \frac{r - r_0}{L} \right)^2 & r_0 \leq r \leq r_0 + \beta L \\
0 & r < r_0
\end{cases}\]

\[r \] is the distance between the origin of the coordinate system and the calculated point in the damping area, and \( \alpha \) is a relevant coefficient. The values of \( \alpha \) and \( \beta \) are both assigned to be 1.0 in this study.

At the water surface, the initial conditions are

\[\phi_s \bigg|_{t=0} = 0, \quad \frac{\partial \phi_s}{\partial t} \bigg|_{t=0} = 0\]

(10)

Eqs. (3) through (10) form a problem with a definite solution under initial and boundary conditions.

**2.2 Solution method**

There are some methods available to solve the above problem expressed as the Laplace equation for the velocity potential. In this study, the problem is solved by transforming the governing differential equation into an integral equation on the boundary using Green’s function method to obtain the velocity potential.

The sum of the basic solution to the Laplace equation and its image with respect to the sea bottom is chosen to form Green’s function:

\[G(P,Q) = \frac{1}{2\pi} \left[ \ln \left( \frac{1}{l} \right) + \ln \left( \frac{1}{l'} \right) \right]\]

(11)

where \( l \) is the distance between the field point \( P \) and the source point \( Q \), \( l' \) the distance between \( P \) and the image point of \( Q \) with regard to the sea bottom. Applying Green’s second theorem to the scattered potential \( \phi_s \) and Green’s function \( G \), the problem may be transformed into the following integral equation:

\[\alpha_0 \phi_s(P) = \int_{\Gamma} \phi_s(Q) \frac{\partial G(P,Q)}{\partial n} - G(P,Q) \frac{\partial \phi_s(Q)}{\partial n} \, d\Gamma\]

(12)

where \( \alpha_0 \) is the solid angle coefficient; \( \Gamma \) is the integral boundary, and \( \Gamma = \Gamma_b + \Gamma_i \), where \( \Gamma_b \) is the mean wet boundary of the body, and \( \Gamma_i \) is the still water surface from the body to the far-field boundary of the artificial beach.
The unknown quantities of Eq. (12) are the velocity potentials on the body surface and its normal derivatives on the free water surface. When the source point is on the body surface, Eq. (12) can be rewritten as follows:

\[
\alpha_0 \phi_b + \int_{r_s} \phi_S \frac{\partial G}{\partial n} d\Gamma - \int_{r_i} G \frac{\partial \phi_S}{\partial n} d\Gamma = \int_{r_s} G \frac{\partial \phi_b}{\partial n} d\Gamma - \int_{r_i} \phi_S \frac{\partial G}{\partial n} d\Gamma
\]

(13)

And when the source point is on the free water surface, Eq. (12) can be expressed as

\[
\int_{r_s} \phi_S \frac{\partial G}{\partial n} d\Gamma - \int_{r_i} G \frac{\partial \phi_S}{\partial n} d\Gamma = \int_{r_s} G \frac{\partial \phi_b}{\partial n} d\Gamma - \int_{r_i} \phi_S \frac{\partial G}{\partial n} d\Gamma - \alpha_0 \phi_S
\]

(14)

Applying the boundary element method, Eqs. (13) and (14) are discretized to obtain a group of linear algebraic equations as follows:

\[
\begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
\phi_b \\
\frac{\partial \phi_b}{\partial n}
\end{bmatrix}
= 
\begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
\]

(15)

It is to be noted that for the pontoon-plate floating breakwater, the mean wet boundary of the body \( \Gamma_b \) in Eq. (15) includes the surface of the plates. Since the boundary element method is employed, the surface of the plates is also divided into a series of discrete panels when some layers of plates are used.

In solving Eq. (15), \( \phi_b \bigg|_{r_s} \) and \( \frac{\partial \phi_b}{\partial n} \bigg|_{r_s} \) at the current time instant are supposed to be known, then \( \phi_b \bigg|_{r_s} \) and \( \frac{\partial \phi_b}{\partial n} \bigg|_{r_i} \) at the next time instant are computed by the numerical method. The water surface elevation \( \eta \) and velocity potentials \( \phi_b \bigg|_{r_i} \) at the next time instant are derived under the free water surface conditions (Eq. (4) and Eq. (5)). The motion displacement and velocity of the body and \( \frac{\partial \phi_b}{\partial n} \bigg|_{r_s} \) at the next time instant are obtained from the motion equations and the body surface condition (Eq. (6)).

### 2.3 Computation of wave forces and mooring forces

The hydrodynamic pressure at any point in the fluid can be expressed as

\[
p = -\rho \frac{\partial \phi}{\partial t}
\]

(16)

where \( \rho \) is the mass density of fluid. The wave forces can be determined by integrating the pressure over \( \Gamma_b \):

\[
F = -\int_{\Gamma_b} \rho \eta d\Gamma
\]

(17)

After obtaining the velocity potentials in the fluid by solving the integral equation, the wave forces may be computed from Eq. (17).

The mooring forces are computed by the catenary theory. Fig. 2 shows the sketch of the mooring chain configuration. The catenary length \( S_c \) of the chain and the length of its vertical projection \( S_z \) are determined by
where $F_x$ is the horizontal component of the mooring force at the top end point $(X, S_z)$ of the mooring chain, $w$ is the unit weight of the chain in water, and $S_x$ is the length of the horizontal projection of $S_c$. The mooring forces are derived from the following equations:

\[
\begin{align*}
\cosh b - 1 &= S_z (\sinh b - b) / (S - X) \\
F_x &= w(S - X) / (\sinh b - b) \\
F_z &= F_x \sinh b \\
b &= S_x / a
\end{align*}
\]  

(19)

where $F_z$ is the vertical component of the mooring force at the top end of the mooring chain, and $S$ is the total length of the chain.

2.4 Motion equations

In this study, the scattered potential is not separated into the diffracted potential and radiated potential, so the motion equations of the body can be written as

\[
\sum_{j=1}^{3} \left[ M_{ij} \ddot{\xi}_j(t) + B_{kj} \dot{\xi}_j(t) + C_{kj} \xi_j(t) \right] = F_k(t) + G_k(t)
\]

(20)

where $F_k \ (k = 1, 2, 3)$ are the horizontal component, vertical component, and moment of the total generalized wave force, respectively; $G_k \ (k = 1, 2, 3)$ are the horizontal component, vertical component, and moment of the total generalized mooring force, respectively; $M$ is the inertia matrix; $B$ is the viscous damping matrix; $C$ is the hydro-restoring matrix; and $\xi_j \ (j = 1, 2, 3)$ are the motion displacements of the floating breakwater, corresponding to sway, heave, and roll, respectively.

The above three coupled differential equations of motion can be reduced to the following second order differential equation:

\[
\ddot{\xi} = f \left( t, \dot{\xi}(t), \ddot{\xi}(t) \right)
\]

(21)
Eq. (21) is solved by applying the fourth order Runge-Kutta method, and the displacement and velocity of the body can be expressed as
\[
\ddot{\xi}(t + \Delta t) = \ddot{\xi}(t) + \Delta t \dddot{\xi}(t) + \frac{\Delta t}{6}(m_1 + m_2 + m_3)
\]
\[
\dddot{\xi}(t + \Delta t) = \dddot{\xi}(t) + \frac{\Delta t}{6}(m_1 + 2m_2 + 2m_3 + m_4)
\]
where \(\Delta t\) is the time step, and
\[
m_i = f(t, \xi(t), \ddot{\xi}(t)) \Delta t
\]
\[
m_2 = f\left(t + \frac{\Delta t}{2}, \xi(t) + \frac{\Delta t}{2} \ddot{\xi}(t), \ddot{\xi}(t) + \frac{m_1}{2} \Delta t\right) \Delta t
\]
\[
m_3 = f\left(t + \frac{\Delta t}{2}, \xi(t) + \frac{\Delta t}{2} \ddot{\xi}(t) + \frac{m_1 \Delta t}{4}, \ddot{\xi}(t) + \frac{m_2}{2} \Delta t\right) \Delta t
\]
\[
m_4 = f\left(t + \Delta t, \xi(t) + \Delta t \ddot{\xi}(t) + \frac{m_2 \Delta t}{2}, \ddot{\xi}(t) + m_3 \Delta t\right) \Delta t
\]

After the displacement and velocity of the floating breakwater at time \(t\) are obtained, the mooring forces are computed according to the displacement-tension relation of the mooring system, and the wave forces and hydro-restoring forces are determined by hydrodynamic analysis. Then the function \(f(t, \xi(t), \ddot{\xi}(t))\) is derived. Using Eqs. (22) and (23), the displacement and velocity of the floating breakwater at time \(t + \Delta t\) are obtained (Chen et al. 2009). The computation is repeated at the next time step as above until the desired termination time is reached.

3 Results and discussion

3.1 Numerical model validation

The numerical model is verified by the results of the experiment on the pontoon floating breakwater conducted by Dong (2009). The experimental cases are as follows: The water depth \(h\) is 0.40 m, the incident wave height \(H_i\) is 0.07 m, and the wave period \(T\) is 1.1 s; the length \(L_p\), the width \(W\), the height \(H\), and the draft \(D\) of the pontoon are 0.44 m, 0.30 m, 0.18 m, and 0.135 m, respectively; the catenary length of the mooring chain \(S_c\) is 0.458 m, the total length \(S\) is 0.907 m, the stiffness is 1.764 kN/m, and the inclination angle \(\gamma\) at the mooring points of the chain is 30°. The lower surface of the floating pontoon is moored to the wave flume bottom by four chains, of which two are at the offshore side, and the other two at the onshore side of the pontoon.

Fig. 3 shows the comparison of motion responses of the pontoon floating breakwater between numerical and experimental results. In the figure, \(\xi\), \(\eta\), and \(\theta\) represent the motion displacements of sway, heave and roll of the pontoon floating breakwater, respectively. It can be seen that the numerical results slightly overestimate the motions compared with the experimental results. However, they all agree well on the whole. In Fig. 3 (a), the numerical result of sway of the floating breakwater is comparatively larger than the experimental result. The reason may be that there is a little difference between numerical and experimental models.
For example, in the test the balance weight is used inside the pontoon to obtain the required draft, while in the numerical model the weight of pontoon is considered uniformly distributed. Furthermore, wave breaking may occur in the experiment, but it is not considered in the numerical model.

Fig. 3 Comparison of motion responses of pontoon floating breakwater between numerical and experimental results

Fig. 4 shows the comparison of mooring forces of the pontoon floating breakwater between numerical and experimental results. In the figure, $F_1$ and $F_2$ denote the offshore side mooring force and onshore side mooring force, respectively. It is shown that the numerical and experimental results basically fit well, except that the peak values of the offshore side mooring force of the numerical result are smaller than those of the experimental result. The difference is mainly because the mooring forces are computed with the static method in the numerical model in which the dynamic actions of fluid on the mooring chains are ignored.

The comparison of transmission coefficient ($C_t$) of the pontoon floating breakwater between numerical and experimental results is shown in Fig. 5. It is seen that both results show a good overall agreement.
3.2 Numerical computation

In this study, floating breakwaters with different layers of horizontal plates are considered to analyze their hydrodynamic properties, namely, the single pontoon floating breakwater, the pontoon floating breakwater with one horizontal plate, and the pontoon floating breakwater with two horizontal plates. The width $W$, height $H$, and relative draft $D/h$ of the pontoon are $0.75h$, $0.45h$, and $0.34$, respectively; the width $W_p$ and thickness $t_p$ of the horizontal plate are $1.25h$ and $0.0125h$, respectively; and the space between two plates and the space from the lower surface of the pontoon to the upper surface of the first plate are both $0.11h$. The total length of the mooring chain $S$ is $1.5h$; the relative drag coefficient, which is defined as the ratio of the drag length to the catenary length of the mooring chain, is $0.98$; and the inclination angle at the mooring point of the chain is $30^\circ$. Based on the above computation parameters, the transmission coefficients, the motion responses, and the mooring forces of the floating breakwaters are calculated.

Fig. 6 shows the computational results of the transmission coefficients of the floating breakwaters with different layers of plates. It can be seen that the relative width $W/L$ has an important influence on the transmission coefficient $C_t$. $C_t$ decreases obviously as $W/L$ increases. This shows that the wave attenuating effect of the floating breakwaters on the short waves is better than that on the long waves. The transmission coefficient of the pontoon floating breakwater with two plates is less than that of the breakwater with one plate, and that of the single pontoon floating breakwater is the largest. This reveals that the horizontal plates installed under the pontoon conduce to the decrease of the wave transmissivity for their contribution to the wave energy dissipation. However, the wave attenuating effect of the floating breakwater increases less significantly as the layer of horizontal plates increases. This is because the wave energy mostly concentrates on the near-water surface, and as the layer of horizontal plates increases, the wave damping effect of the lower plates is weaker on the wave energy.

![Comparison of transmission coefficient of pontoon floating breakwater between numerical and experimental results](image1)

![Transmission coefficients of pontoon floating breakwaters with different layers of plates](image2)
The numerical results of the motion responses of the floating breakwaters with different layers of plates are shown in Fig. 7. It is seen that the motion responses of the pontoon floating breakwaters with one plate or two plates are less than those of the single pontoon floating breakwater. The motion responses of the floating breakwater with two plates are the least. However, as the layer of horizontal plates increases, the motion responses of the floating breakwater decreases less significantly, as that of the wave transmission coefficient does in the above context. The relative width $W/L$ has a rather obvious influence on the motions. The sway and heave motions decrease with the increase of $W/L$, while the roll motion increases as $W/L$ increases.

Fig. 8 shows the computational results of the mooring forces of the floating breakwaters with different layers of plates. It is seen that the changing laws of the mooring forces of the floating breakwaters at the offshore side and onshore side are alike. The mooring forces at both sides decrease with the increase of $W/L$. The mooring force of the floating breakwater with two plates is the smallest, and that of the single pontoon breakwater is the largest, which is corresponding to the motion responses of the floating breakwaters. According to the value, the mooring force at the offshore side is larger than that at the onshore side.

4 Conclusions

A two-dimensional time-domain computational model for the pontoon-plate floating breakwater under wave actions is presented. The hydrodynamic behaviors of the floating breakwater are numerically investigated. The transmission coefficient, the motion responses, and the mooring forces of the pontoon-plate floating breakwater are analyzed. The main conclusions are as follows:
Fig. 8 Mooring forces of floating breakwaters with different layers of plates

(1) By the comparisons of the motion responses, the mooring forces, and the transmission coefficient of the pontoon floating breakwater between numerical and experimental results, it is demonstrated that the present computational model is reasonable.

(2) The relative width \( W/L \) of the pontoon is an important factor influencing the wave transmission coefficient of the pontoon-plate floating breakwater. The transmission coefficient decreases obviously with the increase of \( W/L \).

(3) The horizontal plates can reduce the wave transmission over the floating breakwater. However, the wave attenuating effect of the floating breakwater increases less significantly as the layer of horizontal plates increases.

(4) The relative width \( W/L \) of the pontoon has a comparatively large influence on the motion responses of the floating breakwater. The motions of the pontoon floating breakwater with plates are less than those of the single pontoon floating breakwater. The degree of the decrease of motions becomes small with the increase of the layer of horizontal plates.

(5) Corresponding to the motion responses, the mooring force of the floating breakwater with plates is less than that of the single pontoon floating breakwater. The mooring force at the offshore side is larger than that at the onshore side.

References


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