Numerical Modeling of Wave Interaction with Double Curtain-wall Breakwater

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Abstract

A numerical wave tank (NWT) based on the RANS equations is established by adding source terms into the momentum equation for generating wave and absorbing the reflected waves effectively. The wave dissipation induced by double curtain-wall breakwater and the flow field nearby under the action of regular wave are simulated. The effects of relative immersed depth of barrier on transmission coefficient are analyzed. The numerical results are identical with the experimental data, while they are different a lot from the results of the Lapa formula. The effects of relative width of horizontal plate, relative depth, wave slope are investigated, and a revised formula is presented based on comprehensive verification with both the experiment and numerical results.

Keywords: double curtain-wall breakwater; numerical wave tank; wave transmission coefficient; revised formula

1. Introduction

Double curtain-wall breakwater has become more and more popular in the port hydraulic structures in the recent years. The principle of absorbing wave is that surfer wave-energy is reflected by the partially submerged barriers and interfere the normal motion, which causes the strong turbulence and mixing. Consequently, the wave-energy is partially dissipated and wave height is decreasing to ensure the berth condition. So far, the common approaches to
study the wave attenuation are theoretical analysis, physical model test, prototype observation and numerical simulation. It’s necessary to simplify the actual conditions of the project in theoretical analysis. The transmission coefficient of the vertical thin wall is given by Ursell (1947) for deep water based on modified Bessel function. Wiegel (1960) used the power transmission theory to provide an approximate solution for the transmission and reflection of the single wall. Kriebel and Bollmann (1996) developed the Wiegel’ method, and Losada et al. (1992) studied the topic by eigenfunction expansion method. Porter and Evans (1995) used the multi-term Galerkin method. Different boundary element methods were carried out by Liu and Abbaspour (1982) and Chen et al. (2004). Double immersed walls and multi-walls were proposed and studied by McIver (1985) and Neelamani and Vedagiri (2002). According to similarity theory, the physical models which are scaled have also been widely adopted. The advantages of physical model are visible, but the scale effects are inevitable. For example, it is costly and time-consuming. Tannka (1968) carried out an experimental investigation on performance of two parallel barriers immersed in the water. The relationship between transmission coefficient and relative distance $\lambda/L$ is analyzed. Neelamani and Vedagiri (2002) experimentally studied wave interactions with double immersed vertical barriers, and the influences of the immersed depth, wave heights and wave period were examined. Günaydın and Kabdaşlı (2006) explored the performance of solid and perforated $\pi$-type breakwater. By using field observation, first hand data and relevant information are obtained. The obvious drawback of field measurement is the vast cost of time and money. Sun (1998) conducted a field observation for the performance of a partly immersed vertical barrier breakwater in the Yangtze River. The rapid development of numerical wave tank (NWT) in recent years provides a new approach. Nowadays, the double curtain-wall has achieved good results in lots of engineering applications. However, numerical simulation of wave interaction with absorbing double curtain-wall breakwater is still in its infancy. Therefore, it makes sense to establish a practical numerical wave tank to analyze the hydrodynamic characteristics.

This paper is organized in four parts. Firstly, the user-defined functions for generating and absorbing regular wave in the numerical model are described and verified. Secondly, the propagation of regular wave trains is simulated and compared with analytical results. The influences of relative immersed depth of barrier, relative width of horizontal plate, relative water depth and relative wave height on the transmitted coefficient are numerically investigated. Based on the Wiegel formula, an empirical formula is given according to the above research results.

2. Theoretical Model

Momentum source term method is adopted for generating wave and absorbing energy in NWT. It was originally presented by Mayer et al. (1998). Wang and Liu (2005) extended the wave-maker method and applied it to the numerical study of water wave based on the high order Boussinesq equations. Some applications of the numerical wave tank in wave-structure interactions were reported, such as Zhou et al. (2005), Lu et al. (2007), Liu et al. (2007) and Sun (2010). This study investigated the hydrodynamic characteristics of double curtain-wall breakwater under the loading action of regular waves. Considering the incompressible and viscous flow, primary governing equations are the well-known Reynolds-averaged Navier-Stokes (RANS) equations. Source term is added into the momentum equation, which can generate and absorb waves. The volume of fluid (VOF) method is used for ‘tracking’ the free surface variation. The continuity equation and filtered Navier-Stokes (N-S) equations are as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
\]

\[
\frac{\partial (\rho u)}{\partial t} + u \frac{\partial (\rho u)}{\partial x} + v \frac{\partial (\rho v)}{\partial y} = \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{\partial p}{\partial x} + S_x
\]

\[
\frac{\partial (\rho v)}{\partial t} + u \frac{\partial (\rho v)}{\partial x} + v \frac{\partial (\rho v)}{\partial y} = \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{\partial p}{\partial y} - \rho g + S_y
\]
For two dimensional NWT, \( x \) and \( y \) represent the Cartesian coordinate grid; \( \rho \) is the fluid density; \( t \) is the time; \( u \) is the transversal velocity component; \( v \) is the vertical velocity component; \( \mu \) is the turbulent viscosity; \( g \) is the gravitational acceleration; \( S_x \) and \( S_y \) are the momentum source terms in the \( x \)-direction and \( y \)-direction, respectively. The computational domain is divided into four parts: wave maker zone; relaxation zone; work zone and sponger zone, as illustrated in Fig.1.

\[
\begin{align*}
\text{Analytical relaxation approach is applied in the solution of N-S equation. The wave generation and absorption are implemented by updating velocity and pressure directly at each step, which can be expressed as:} \\
\mathbf{u}_m &= C \mathbf{u}_c + (1 - C) \mathbf{u}_i \\
\mathbf{v}_m &= C \mathbf{v}_c + (1 - C) \mathbf{v}_i \\
\mathbf{p}_m &= C \mathbf{p}_c + (1 - C) \mathbf{p}_i
\end{align*}
\]

The variables with the subscript \( c \) are the calculated values from N-S solver, variables with the subscript \( i \) are the incoming wave variables. \( C= C(x) \) is the relaxation function related to spatial coordinate in each zone. At two ends of the wave maker zone, function \( C \) satisfies:

\[
[C]_{\text{xmin}} = 1, ~ [C]_{\text{xmax}} = 0 ;
\]

In the relaxation zone, the purpose of the function \( C \) is to eliminate the reflected wave from work zone, which satisfies:

\[
[C]_{\text{ymin}} = 0, ~ [C]_{\text{ymax}} = 1 ;
\]

In the sponger zone, function \( C \) is used to absorb the right-going waves out of work zone to prevent wave reflection at the boundary, function \( C \) satisfies:

\[
[C]_{\text{zmin}} = 1, ~ [C]_{\text{zmax}} = 0 ;
\]

3. Numerical wave tank

3.1 Computational domain and discretization method

The NWT is 425m long and 24m high. The length of the wave maker zone, relaxation zone, work zone and the sponger zone are 75m, 75m, 200m and 75m, respectively. The upper part of the tank is full of air and the lower part is filled with water. The coordinates \((0,0)\) is on the far left of the free surface. It’s necessary to refine the mesh near the free surface. At the bottom and the right end, no-slip wall boundary condition is imposed by one type of immerse boundary method. The leftmost of computational domain is symmetry boundary to satisfy non-penetrating condition. The top boundary is pressure outlet boundary.

The NWT is developed on the basis of the commercial package FLUENT by the implementation of user defined function (UDF). The segregated solver, VOF tracking technique, standard k-\( \varepsilon \) turbulence model and pressure implicit with splitting of operators (PISO) are adopted in the numerical simulation.

3.2 Model verification

The experiments are conducted in the tank of Ocean Engineering Center at Hohai University in Nanjing,
China. The wave is generated by the paddle. There are porous slopes for energy dissipation at both ends of the wave tank. In physical models, wave transmission coefficients were measured under regular waves. The details about wave high, wave period and wave lengths are shown in Table 2.

Table 2. Wave conditions in laboratory experiments

<table>
<thead>
<tr>
<th>water depth d/m</th>
<th>wave elements once a hundred years number</th>
<th>wave elements once fifty years number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H/m</td>
<td>T/s</td>
</tr>
<tr>
<td>17.03</td>
<td>a1</td>
<td>2.96</td>
</tr>
<tr>
<td>15.68</td>
<td>b1</td>
<td>2.75</td>
</tr>
<tr>
<td>13.90</td>
<td>c1</td>
<td>2.48</td>
</tr>
<tr>
<td>11.18</td>
<td>d1</td>
<td>2.20</td>
</tr>
<tr>
<td>10.25</td>
<td>e1</td>
<td>1.94</td>
</tr>
</tbody>
</table>

The exact same wave conditions are used in the numerical simulation. The accuracy of wave in the work zone must be guaranteed. Taking wave case a1 as an example, the wave surfaces at x=170m is monitored. Comparisons of measured and simulated surface elevation of the two points are shown in the Fig.2, indicating a great agreement between numerical simulation and experimental measurement.

Fig. 2 Comparison of time series of surface elevation at x=170m between numerical result and theoretical result

4. Impacts on Transmission Coefficient

4.1 Structure of the breakwater

As shown in Fig.3 and Fig.4, the section I of a double curtain-wall structure consists of the two curtain-walls, beam, longitudinal, two pairs of oblique piles and breast wall. There are three sections of the breakwater. Taking section I as an example, the elevation of breast wall is +9.5m, the bottom of the water is -11.5m, the horizontal plate is +7.05m, the beam is +3.9m, and the two barriers have the same bottom level -2.0m. The distance of bent is 5.0m, and 4 inclined-piles with a slope of 35:1 support every bent. The barrier bottom-level is -2.4m in section II, and the barrier bottom-level is -3.2m in section III.
4.2 Flow field among the breakwater

The structure is simplified in the case of numerical simulation. Only the two vertical barriers, horizontal plate and breast wall are retained. Unstructured grid is adopted at the range of $x=195\text{m}$ and $x=217\text{m}$, in other words, five meters before and after the breakwater. Structured grids are used with grid size $\Delta x=0.4\text{m}$ in the wave propagation direction and $\Delta y=0.1\text{m}$ in the vertical direction near the liquid level. In other range of the vertical direction, grid size $\Delta y=0.1\text{m}$ is chosen. The amount of mesh is 217499 with a minimum area of 0.0025$m^2$. The velocity vector and wave surface around breakwater within 7s for the case a1 is shown in Fig.5, showing the wave progress with a wave period being 6.73s at different time levels.

As can be seen from Fig.5, the water in the upper part is moving upwards with a high-speed when the wave meets with the front barrier. However there is no wave overtopping, which indicates the height of the breast wall is reasonable. Part of the water is reflected, and the other part passes the front breakwater. At least, only a little water passes over the back barrier. Most of the water is whirling, which is the main causes of energy dissipation. The shift of the water surfer behind the barrier is small, and the wave-height is less than 1m in all numerical cases.

4.3 Effects of relative immersed depth of barrier
The wave transmission coefficients of three sections with different wave conditions are studied. The effects of relative immersed depth of barrier ($t/d$) on transmitted coefficient are investigated (see Fig.6). It’s clear that it’s effective to reduce the transmitted coefficient by increasing the relative immersed depth of barrier. This fact can be due to two reasons. On the one hand, incident wave energy becomes smaller with increasing the relative immersed depth of barrier. On the other hand, the vertical scale of the swirl is larger while the swirl-dissipation is increasing. Through statistics and analysis, a 10% increase of relative immersed depth of barrier can reduce the transmission coefficient about 10%.

Fig.6 shows the comparisons between experimental data, numerical results and values from Lapa formula. It can be seen that the numerical results agree well with experimental data, while both of them are different from the results of the Lapa formula. The numerical results and Lapa formula results follow the same trend as relative immersed depth of barrier increases. It can be concluded that the suitability of Lapa formula is limited. The Wiegel formula and Kriebel formula are not suited to the double curtain-wall breakwater. Therefore, it is necessary to study and bring forward a transmission coefficient formula for the double curtain-wall breakwater.

![Fig.6 The effect of relative immersed depth. (∆, Lapa formula; ○, Experimental; □, Numerical)](image)

4.4 Effects of relative width of horizontal plate

The transmitted coefficient is not only influenced by relative immersed depth of barrier, but also by relative width of horizontal plate ($B/L$), relative water depth($d/L$), relative wave height($H/L$) and so on. The two dimensional NWT is used to study the effects of these parameters. The water-depth and wave conditions are rearranged. The tank has a still water depth of 10m. The wave-height is 1.2m, 1.6m, 2.0m and 2.4m, respectively. The wave periods are 5.0s, 5.5s, 6.0s and 6.5s. So, there are 16 wave cases. The width of horizontal plate is 8m, 10m, 12m and 14m. As the relative immersed depth of barrier has been studied above, the immersed depth of barrier is only 2m. There are 4 kinds of sections. To be sure, the breast wall is high enough to reflect the wave completely, and the effect of overtopping is not considered.

The effect of relative width of horizontal plate on transmitted coefficient is shown in Fig.7. The transmitted coefficient is decreasing with an increasing of relative width of horizontal plate in the range of $0.159 \leq B/L \leq 0.401$. When the relative width of horizontal plate increases, the larger vertical scale swirl largely enhances the whirl-dissipation.
4.5 Effects of relative water depth

Fig. 8 shows the effects of relative water depth ($d/L$) on transmitted coefficient. When the $d/L$ falls in the range of 0.199–0.287, the transmitted coefficient is decreasing as the increasing of relative water depth. There is no doubt that the relative water depth is a main influential factors.

4.6 Effects of relative water depth

The transmitted coefficient in relations with the relative water depth is shown in Fig. 9. The transmitted coefficient is not changed obviously when the relative water depth is increased from 0.024 to 0.069. The results indicate that the influence of the relative water depth is negligible.
4.7 Revised formula of transmission coefficient

Only relative immersed depth of barrier is considered in previous formula, ignoring the effects of relative width of horizontal plate, relative water depth and relative wave height. As discussed above, the influences of these parameters cannot be neglected. Based on the Wiegel formula, a revised formula is proposed by half experience and half theory. The power transmission theory was derived by Wiegel(1960) based on three assumptions. The transmission coefficient formula as follows:

\[ K_t = \frac{2k(d-t_o) + \sin h2k(d-t_o)}{2kd + \sin h2kh} \]  

(10)

In this study, the breakwater has double curtain-wall. Two assumptions are employed. Firstly, the interactions between the two barriers are ignored. The energy dissipation after the two barriers is overlaid in the form of multiplying the double \( K_t \). Secondly, a corrected wave-energy factor \( \alpha \) is introduced into the expression, by considering the impact of relative width of horizontal plate, relative water depth and relative wave height.  

\[ \alpha = f(B/L, \ d/L, \ t_o/d, \ H/L) \]  

(11)

The corrected formula is written as

\[ K_t = \alpha \cdot \frac{2k(d-t_o) + \sin h2k(d-t_o)}{2kd + \sin h2kh} \]  

(12)

The front and back barriers have the same immersed depth, so

\[ K_t = \alpha \cdot \frac{2k(d-t_o) + \sin h2k(d-t_o)}{2kd + \sin h2kh} \]  

(13)

In general, the corrected factor \( \alpha \) can be estimated by

\[ \alpha = \sqrt{\left( k_i \cdot \frac{B}{L} + k_i \cdot \tanh \frac{2\pi d}{L} + k_i \cdot \frac{H}{L} + k_i \cdot \frac{e^2}{2\pi} \right)^{\frac{2}{3}}} \]  

(14)

Combination of Equations (4) and (6) gives

\[ K_t = \sqrt{\left( k_i \cdot \frac{B}{L} + k_i \cdot \tanh \frac{2\pi d}{L} + k_i \cdot \frac{H}{L} + k_i \cdot \frac{e^2}{2\pi} \right)^{\frac{2}{3}}} \cdot \frac{2k(d-t_o) + \sin h2k(d-t_o)}{2kd + \sin h2kh} \]  

(15)

Based on lots of test data, a corrected formula is given after nonlinear fitting calculation.

\[ K_t = \sqrt{\left( -1.627 \cdot \frac{B}{L} - 0.934 \cdot \tanh \frac{2\pi d}{L} - 1.246 \cdot \frac{H}{L} + 1.720 \cdot \frac{e^2}{2\pi} \right)^{\frac{2}{3}}} \cdot \frac{2k(d-t_o) + \sin h2k(d-t_o)}{2kd + \sin h2kh} \]  

(16)

Comparison between calculated values and Lapa formula (see Fig.10) show that the Lapa formula results are obviously larger. The correlation of calculated values and revised formula is shown Fig.11, indicating a good agreement.
As shown in Fig.12, the Lapa formula results over-predict the experimental measurements. However, the difference between these two results is nearly constant. It can be seen from Fig.13 that the revised formula agrees well with the experimental values when the transmitted coefficient is less than 0.4. There is great deviation between the revised formula results and experimental results when the transmitted coefficient is greater than 0.4, and further research is needed.

5. Conclusion

A vertical two-dimensional NWT is established to study wave dissipation and transmission coefficient of a double curtain-wall breakwater. A series of regular waves are simulated to validate the capability of wave generating and absorbing modules. It is shown that the NWT is efficient and stable. The velocity vector and wave surface around the breakwater are well reproduced. Relative immersed depth of barrier has a significant impact on transmission coefficient. A 10% increase of relative immersed depth of barrier can reduce the transmission coefficient about 10%. The influences of relative width of horizontal plate, relative water depth and relative wave height are also numerically analyzed. The analysis indicates that relative width of horizontal plate and relative water depth are main influential factors besides relative immersed depth of barrier, while relative wave height has less impact on transmission coefficient. A revised formula is given according to the four impact factors. Comparing with the experimental values and numerical results, a good agreement implies that the revised formula could reasonably predict transmission coefficient for a double curtain-wall breakwater.
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References


