Numerical Modeling of Solitary Wave Interaction with a Submerged Perforated Barrier

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ABSTRACT

In this paper, we investigate the interaction between an isolated solitary wave and an underwater perforated barrier numerically. With the advantages on enhancing water circulations and sediment movements, the perforated barrier is considerably more cost effective and less environmental impact than the conventional hard structures. The numerical results are calculated by a two-dimensional volume of fluid (VOF)-type model which solves the Reynolds-Averaged Navier-Stokes (RANS) equations and the nonlinear $k$-$\varepsilon$ turbulence closure model. The main attentions would be paid on tracing the trajectories of fluid particles around the object to help understand possible sediment movements for suspended loads and on evaluating the wave reflection, transmission, and dissipation coefficients using the energy integral method.

Keywords: Solitary wave; Submerged; Perforated barrier; Breakwater; Energy dissipation; RANS model
fields separately without the effects by other incoming waves.

Due to the recent rise of environmental awareness, the type and size of coastal structure would become an important factor to coastal engineers for aesthetic and environmental concerns. Most traditional breakwater constructed by a large amount of concrete and rubble mound, which is not cost-effective and not environmental friendly. Also, in some circumstance those structures may prevent the water circulation, fish passage and even decline the water quality near the coast (Rageh and Koraim, 2010).

With advantages of enhancing the sediment movement, water circulation and the exchange between the open sea and sheltered areas, wave barriers in the form of thin, rigid, vertical, and surface-piercing structures are considered an alternative for coastal protection (Huang et al., 2011). Many studies have performed the wave dynamics and estimated the functional efficiency of solid (Liu and Al-Banaa, 2004) and perforated (Huang and Yuan, 2010) surface-piercing barrier under a solitary wave. Compared to surface-piercing barrier, to our knowledge, the studies on interaction between a solitary wave and a submerged solid/slotted barrier were relatively rare in literature. Wu et al. (2012) used PIV measurement and RANS model to quantitate the velocity and turbulence fields in the vicinity of a bottom-mounted solid barrier under a strong breaking solitary wave.

In our previous study (Wu et al., 2011), we present the wave hydrodynamics for a breaking solitary wave propagation over a submerged slotted barrier using a RANS model to illustrate the free surface displacement and vortex shedding via changing and locations within the water column of the barrier. The main objective of this paper is to extend our previous work to further discuss the trajectories of fluid particle around the structure to help understand the possible sediment movement for suspend loads and the evaluation of the breakwater’s functional efficiency using energy integral method instead of basing on wave height information only for purpose of engineering designs.

2. Numerical Model

The computational model, named COBRAS (COrnell BReaking And Structure), is a two-dimensional numerical scheme which solves the Reynolds-Averaged Navier-Stokes (RANS) equations for describing the mean (ensemble average) flow field with the nonlinear $k$-$\varepsilon$ equations for the turbulent kinetic energy ($k$) and the turbulent dissipation rate ($\varepsilon$). The model solves the RANS equations using the finite-difference two-step projection method (Chorin, 1968). The volume of fluid (VOF) method was constructed in the model for tracking the free surface motion originally proposed by Hirt and Nichols (1981). The active absorption inflow boundary condition was utilized in the upstream boundary to avoid re-reflection (Torres-Freyermuth et al., 2010). Not only could this generating-absorbing boundary condition absorb the reflected long wave, it could minimize the computation domain. Detailed information about the numerical implementation is given in the study of Lin and Liu (1998).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>List of the location for three various perforated barriers.</th>
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<tr>
<td>Type</td>
<td>$d_1$ (cm)</td>
</tr>
<tr>
<td>A</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
</tr>
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Fig. 1 Details of the numerical wave flume and the perforated barrier (a): computational domain; (b): close view of the perforated barrier.
3. Results and Discussions

3.1 Numerical Setup

A numerical wave flume consists of $-2.5 \leq x \leq 1.0$ m and $0 \leq y \leq 0.3$ m. For simplicity, a solitary wave with a wave height ($H$) of 6.3 cm in a constant water depth ($h$) of 18.0 cm was used. Structured and uniform rectangular grids of $\Delta x = \Delta y = 1$ mm are employed for calculation accurate and efficient. The simulation time is 10 s, and the corresponding time step is automatically adjusted during calculations. Figure 1 (a) shows the schematic diagram of the numerical wave flume. The slotted barrier with width 2 cm and length 10 cm (i.e. the aspect ratio equals five), in superficial not volumetric, is composed by three impermeable and same scale elements, yet the porosity ($n$) is determined by a gap spacing ($c$) and distance ($b$) of each element (Fig. 1 (b)). A total of six different porosities of the slotted barrier, i.e., $n=0$, 0.04, 0.10, 0.19, 0.31 and 0.40, are calculated. Besides, three various locations of wave barrier are considered (see Table 1) by moving the vertical site within the constant water depth. The reference time ($t = 0$ s) is defined as when the wave crest of solitary wave arrives at $x = -0.7$ m.

3.2 Trajectories of Fluid Particles around the Perforated Barrier

From the viewpoint of engineering practices, the induced vortices and corresponding turbulence mainly contribute to sediment transport then result in scouring near the toe of breakwaters, which may even affect the integrity and stability of coastal structures. To acquire more information on the possible transportation of sediment, the fluid particles with initial locations close to the barrier were determined in order to trace their trajectories of each particle. Although the motion of fluid particles are distinct from that of the real sediment physically, it still might provide an insight into the possible sediment movement in suspension near the barrier. Figure 2 and 3 illustrates the initial positions of the fluid particles around the barrier respectively for Type $A$ and $B$ condition. Those particles are released at the same time from $t = 0.0$ to $2.0$ s with an identical time interval of 0.01 s. Due to page limitation, here we only show six trajectories of fluid particles for three different porosities, i.e., $n=0$, 0.19 0.40. Note that the schematic diagram of the barrier is plotted only for the porosity being 0.40. The symbols “circle” and “triangle” in Figs. 4–7 depict the initial and ending position of each marked fluid particle, respectively.

For the bottom-standing case (Type $A$), as can be seen in Fig. 4, the fluid particle six ($P_06$) may bypass the barrier to the downstream while the porosity is zero and 0.19, but for the larger porosity case ($n=0.40$), the particle may across the barrier then move downstream. Especially for the particle seven ($P_07$) with the porosity being 0.19, the particle moves forth to the downstream then comes back to the upstream due to the adverse flow caused by the wave crest past over the barrier. For the particles close to the lee side of the barrier, the particle eight ($P_08$) for all cases may finally transport to the onshore direction. For those particles near the seafloor and the weather side of the barrier ($P_01$&$P_02$), those particles may be obstructed by the obstacle while the barrier is solid (Fig. 5). On the contrary, those particles may across the barrier if the barrier is perforated. When the porosity is 0.40, those particles move forth and back to the original upstream location. Interestingly, for the particle thirteen ($P_{13}$) with the porosity respectively equal to zero and 0.19, the particle may lift near the free surface and then propagate in opposite direction, the fluid particle for solid barrier come back upstream and the other one transport downstream.

For the Type $B$ perforated barrier, as can be seen in Fig. 6, the particle six ($P_{06}$) that near the weather side of the slotted barrier bypass the barrier and then transport downstream as the porosity equals zero. If the barrier is perforated, as expected, the particle may just across the barrier to the onshore direction, which can enhance the water circulation. For the particle
eight ($P_{08}$) who closes to the lee side of the barrier, all of them move downstream. For those fluid particles near the seafloor move from the offshore to the onshore direction directly because no obstacle can obstruct the transportation (Fig. 7).

Fig. 2 Initial positions of fluid particle around the Type A perforated barrier.

Fig. 3 Initial positions of fluid particle around the Type B perforated barrier.

Fig. 4 Simulated particle trajectories ($P_{06}$-$P_{08}$) from $t=0.0$ to $2.0 s$ with time interval of 0.01s for the Type A perforated barrier.

Fig. 5 Simulated particle trajectories ($P_{11}$-$P_{13}$) from $t=0.0$ to $2.0 s$ with time interval of 0.01s for the Type A perforated barrier.

Fig. 6 Simulated particle trajectories ($P_{06}$-$P_{08}$) from $t=0.0$ to $2.0 s$ with time interval of 0.01s for the Type B perforated barrier.
3.3 Energy Reflection, Transmission and Dissipation

We also evaluate the functional efficiency of the submerged perforated barrier through the calculations of wave reflection, transmission and dissipation (RTD) coefficients using the energy integral method proposed by Lin (2004), based on integration of energy flux, instead of using wave height information only. Using this method to determine RTD coefficients is more appropriate during the wave-structure interaction under the process of vortex shedding and wave breaking. This method has been frequently used in literatures to estimate the functional efficiency of coastal structures under a solitary wave (Lin, 2004; Lin and Karunarathna, 2007; Wu et al., 2012).

In this section, except the bottom-standing (Type A) and totally submerged slotted barrier (Type B), we further consider another condition that just put the slotted barrier to fit the still water level (Type C), yet the wave still can overtop it. Detailed configuration of the perforated barrier can be found in Table 1. All energy coefficients against the porosities under identical wave condition are plotted together as shown in Fig. 8.

We can find that for all Type A–C, the reflected energy coefficients decrease with increasing the porosity value, and the transmitted energy coefficients are found to increase with increasing porosity of slotted barrier. However, there is no significant variation in the reflected and transmitted energy coefficients for these three types of perforated barrier. This is because that a solitary wave can be thought as a very long wave such that the fluid particles motion are almost uniform throughout the water column. However, for the energy dissipation, the Type C barrier performed a larger value than the others did, which is up to 40% for solid barrier. The trend of energy dissipation coefficient is decreasing with increasing the porosity.

Fig. 7 Simulated particle trajectories ($P_{11}$–$P_{13}$) from $t=0.0$ to $2.0s$ with time interval of $0.01s$ for the Type B perforated barrier.

![Effects of porosity of the perforated barrier on the energy reflection, transmission and dissipation coefficients.](image)

4. Concluding Remarks

In this paper, we present a solitary wave propagation over a submerged perforated barrier using a two-dimensional VOF-type numerical model, which solves Reynolds-Averaged Navier-Stokes (RANS) equations coupled with the $k$-$\varepsilon$ turbulence closure model. The slotted barrier is composed by three impermeable and same scale elements, so the porosity can be determined by a gap spacing and distance of
each element. Six porosities from 0.0 to 0.40 are calculated. We alter the three different vertical location of perforated barrier within the water depth in order to check their difference in hydraulic performance. The slotted barrier may help enhance the sediment movements in suspension, which is validated by tracing the trajectories of the marked fluid particles around the slotted barrier. All the energy coefficients for altering the vertical displacement of the barrier are almost the same because the horizontal velocity distribution of the solitary wave is nearly uniform. Future study on using a set of submerged slotted barriers is warranted in order to optimize their functional efficiency.

Acknowledgements

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References