Wave transmission at low-crested structures

Oki, Muhammad Hafiz, Martin, Risky Ayu

Abstract. The transmission of wave energy through structures is a significant factor in coastal engineering, especially in the design of breakwaters. The effectiveness of such structures is crucial for mitigating erosion and controlling wave energy. This paper focuses on the wave transmission through artificial reefs, serving as a low-cost solution for coastal protection. The study utilizes DualSPHysics, an SPH software, to simulate wave interactions within artificial reefs. The outcomes of this research can aid in the optimization of breakwater design and provide insights into the effectiveness of artificial reefs as a low-cost coastal protection measure.

1 Introduction

The transmission of wave energy through coastal structures is a critical aspect of coastal engineering. Breakwaters are designed to dissipate wave energy and prevent coastal erosion. Artificial reefs, as a low-cost option, have been proposed for coastal protection. This research aims to assess the wave transmission at low-crested structures, with a specific focus on artificial reefs. DualSPHysics, an SPH software, is employed to simulate wave interactions within artificial reefs. The results of this study will provide insights into the effectiveness of artificial reefs as a low-cost coastal protection mechanism.

2 Smoothed particles hydrodynamics (SPH)

The Smoothed Particle Hydrodynamics (SPH) method is a numerical technique that has been widely used in coastal engineering applications. It uses a kernel function to interpolate the properties of the fluid between the particles. This kernel function is used to calculate the forces acting on each particle and to model the fluid behavior. The SPH method is particularly useful for simulating complex wave phenomena, which is crucial for coastal engineering research.
\[ p = b \left( \frac{\rho}{\rho_0} \right)^\gamma - 1 \]

where 
\[ b = c_0^2 \frac{\rho_0}{\gamma} \] \[ \gamma = 7 \] \[ \rho_0 \] \[ c_0 = c(\rho_0) \]

Lastly, particle of interest and function with respect to particle.

In this work, we consider the latest features exist in DualSPHysics software and its website: dual.sphysics.org/... available in the work of Dominguez et al. Here a brief validation on wave generation is presented, however, in the present study, the more complete formulations and weakly compressible order wave generation to the physical laboratory.

The SPH method approximates the fluid properties by using a set of discrete particles. The properties of each particle using a kernel function \( \Psi \) is calculated by averaging the properties of the neighbouring particles where \( \rho_i \) is the density of particle \( i \), \( \mathbf{v}_i \) is the velocity, \( \mathbf{p}_i \) is the pressure, \( \mathbf{W}_{ij} \) is the diffusion term between particles, \( \Pi_{ij} \) is the viscosity term and \( \mathbf{g} \) is the gravity acceleration.

The simulation domain is configured as shown in a sketch in Fig. 1 showing the lateral view of a 100 m long flume equipped with a piston type wavemaker. The last 25 m of the other end of the flume is set to be a damping zone to avoid wave reflection.

3 Simulation setup

The SPH method is based on the Navier-Stokes equations, which describe the behaviour of fluid flows.

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3.1 Artificial reef geometry

Artificial reef geometry

where \( \rho_0 \) is the speed of sound at the reference density. Note that the damping process is done numerically using a set of discrete particles. The properties of each particle are calculated by averaging the properties of the neighbouring particles.

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The dimension of the artificial reef unit is illustrated in Fig. 2. The breakwater structure in this study was formed by arranging the reef units in a specific pattern, as shown in Fig. 3. The units were assumed to be interconnected in a rigid manner, although in reality, they may be linked using a kind of durable rope, allowing for slight movement upon impact by waves while maintaining contact. The structure movement is constrained in this simulation.

To assess the impact of different arrangements on wave transmission, two configurations were tested. The first configuration (Fig. 3(a)) involved arranging the units in a pattern coloured in blue, with subsequent units in the same row following the same pattern. In the second configuration (Fig. 3(b)), the cube row located behind the red pattern was shifted forward by 0.5 m. This shifted grid arrangement resulted in smaller cavities within the structure while maintaining the same number of unit cubes, which can be visually evidenced by the side views facing the incoming waves.

### 3.2 Numerical parameters

Table 1 presents the complete list of SPH numerical parameters employed in these simulations. The parameter \( \text{coeff} \) represents the ratio of smoothing length to the initial inter-particle distance \( (D_p) \). The second-order symplectic position Verlet integration scheme [5] was employed for time integration, with a variable time step size computed based on the maximum velocity and acceleration at each step.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value/option</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{coeff} )</td>
<td>1.5</td>
</tr>
<tr>
<td>( D_p )</td>
<td>0.075 m</td>
</tr>
<tr>
<td>( \text{StepAlgorithm} )</td>
<td>Symplectic</td>
</tr>
<tr>
<td>( \text{Kernel} )</td>
<td>5th order Wendland</td>
</tr>
<tr>
<td>( \text{ViscoTreatment} )</td>
<td>Artificial viscosity (( \alpha = 0.05 ))</td>
</tr>
<tr>
<td>( \text{ViscoBoundFactor} )</td>
<td>0</td>
</tr>
<tr>
<td>( \text{DensityDT} )</td>
<td>Fourtakas (full)</td>
</tr>
<tr>
<td>( \text{DensityDTvalue} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( \text{Shifting} )</td>
<td>Yes (full)</td>
</tr>
<tr>
<td>( \text{ShiftCoef} )</td>
<td>-2</td>
</tr>
<tr>
<td>( \text{ShiftTFS} )</td>
<td>2.75</td>
</tr>
<tr>
<td>( \text{TimeMax} )</td>
<td>40 s</td>
</tr>
</tbody>
</table>
The different arrangements of the reef units composing the breakwater structures: (a) regular grid and (b) shifted grid.

The 5th-order Wendland kernel \([4]\) was selected as the smoothing kernel function. Artificial viscosity \([7]\) was incorporated to reduce the numerical instability with a tuning value of \(\alpha = 0.05\), while the boundary particles were excluded from the viscosity term to prevent excessive boundary friction. The force computation included the density diffusion term \((\text{DensityDT})\) proposed by Fourtakas et al. \([8]\) to achieve a smoother pressure field. The shifting algorithm \([9]\) was activated with a coefficient of -2 and a free-surface threshold value of 2.75 to maintain a consistent particle distribution and ensure the accuracy of the SPH interpolation. Lastly, \(\text{TimeMax}\) refers to the overall duration of the simulation which is 40 seconds. This time is equivalent to generating waves eight times.

3.3 Wave parameters

Two different wave heights \((H)\) were tested in this study: 0.5 m and 1.5 m, with a fixed wave period \((T)\) of 8 s and a water depth \((d)\) of 3 m. Both waves are classified as intermediate depth waves and are best described at least by the second order wave theory, as shown in Fig. 4. Therefore, the piston motion was determined in accordance with the second order wave theory. The wave height of 1.5 m is close to the breaking wave limit, and in fact, the simulation demonstrated a spilling-type breaking condition, which will be presented later. As the reef was utilized as a breakwater structure, the breaking wave condition was used to evaluate the effectiveness of the reef in reducing high-energy waves. Furthermore, a non-breaking wave with \(H = 0.5\) m was also tested to provide a more comprehensive analysis.

4 Results and discussion

4.1 Numerical performance

This section briefly explains the numerical performance of DualSPHysics software used in this study. All simulations were performed on a personal computer (PC) with:

- Intel® Core™ i7-9700K @ 3.60GHz CPU,
- NVIDIA GeForce RTX 2080 Ti GPU.

The PC was utilized to simulate all six cases, as listed in Table 2, which included two different wave heights tested against two reef configurations along with a water-only case for benchmarking purposes.
Table 2. Computational performance of the SPH simulation.

<table>
<thead>
<tr>
<th>$H$ (m)</th>
<th>Case</th>
<th>Boundary particles</th>
<th>Fluid particles</th>
<th>Total particles</th>
<th>SPH steps</th>
<th>Runtime (s)</th>
<th>Runtime (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Water only</td>
<td>321,300</td>
<td>2,338,050</td>
<td>2,659,350</td>
<td>111,051</td>
<td>18,639</td>
<td>5.18</td>
</tr>
<tr>
<td></td>
<td>Regular reef</td>
<td>344,085</td>
<td>2,312,823</td>
<td>2,656,908</td>
<td>112,461</td>
<td>18,830</td>
<td>5.23</td>
</tr>
<tr>
<td></td>
<td>Shifted reef</td>
<td>345,825</td>
<td>2,310,505</td>
<td>2,656,330</td>
<td>113,041</td>
<td>18,967</td>
<td>5.27</td>
</tr>
<tr>
<td>1.5</td>
<td>Water only</td>
<td>321,300</td>
<td>2,338,050</td>
<td>2,659,350</td>
<td>120,932</td>
<td>20,341</td>
<td>5.65</td>
</tr>
<tr>
<td></td>
<td>Regular reef</td>
<td>344,085</td>
<td>2,312,823</td>
<td>2,656,908</td>
<td>133,543</td>
<td>22,375</td>
<td>6.22</td>
</tr>
<tr>
<td></td>
<td>Shifted reef</td>
<td>345,825</td>
<td>2,310,505</td>
<td>2,656,330</td>
<td>131,697</td>
<td>22,038</td>
<td>6.12</td>
</tr>
</tbody>
</table>

4.2 Effect on wave profile

$$K_t = \frac{H_t}{H_i}$$

Fig. 5. Surface elevation (m) over time (s) for different wave heights $H$.

Fig. 6. Wave transmission coefficient $K_t$ against $H/(gT^2)$.
4.3 Effect on velocity field

This section displays visual representations of the velocity field of the fluid body obtained from the numerical simulations. Fig. 7-8 show the velocity field for wave heights of 0.5 m and 1.5 m, respectively. The plots illustrate the wave behaviour as it passes through the artificial reef breakwater. Each frame in the figures depicts the comparison of three simulations: without structure, regular reef, and shifted reef. The velocity in the x-direction is represented by the coloured field, with red indicating right-hand side direction and blue indicating left. It should be noted that the waves approach the reef from the left and the colour scale varies between Fig. 7-8. Additionally, we took the last incoming wave for all comparisons.

Fig. 7. Velocity field comparison for $H = 0.5$ m at (a) $t = 32$ s and (b) $t = 34$ s. Fig. 7 (a) depicts the simulation results for a 0.5 m wave height at time $t = 32$ s, which corresponds to the moment when the wave has just passed through the breakwater. It can be observed from the velocity field that the presence of the artificial reef has caused an overall reduction in the fluid velocity. Additionally, the flow through the regular reef is relatively faster compared to the shifted reef owing to the larger void within the latter. At $t = 34$ s (Fig. 7 (b)), the velocity of the transmitted wave is inherently reduced, with the shifted reef providing a slightly better reduction in the fluid velocity field.

Fig. 8 illustrates the breaking wave approaching the reef structure in more detail. The spilling-type breaking wave is clearly visible, starting to hit the structure at $t = 30.2$ s. As shown in Fig. 8 (a), the splashy wave tip gradually creeps over the reef crest, demonstrating the capability of SPH in simulating free surface flow. By $t = 30.8$ s (Fig. 8 (b)), approximately half of the wave body has passed the structure. It is evident that the flow velocity under the reef crest is significantly reduced by the structure, with the shifted reef configuration again showing better performance. However, the overtopping wave velocity remains high and is not much affected. After a few seconds ($t = 33.6$ s), the velocity field becomes similar to that of the wave without structure, albeit still with lower velocities. Ultimately, the shifted reef configuration successfully removes the breaking wave, resulting in a normal wave.

It is worth noting that the artificial reef effectively reduces both wave height and velocity, as shown previously. However, further testing under varying wave conditions is required to fully assess its effectiveness. As the wave period and wavelength in this study were relatively long, the reduction of long wave transmission by the artificial reef was not as significant as expected. Nonetheless, the shifted reef configuration demonstrated better performance in reducing both wave height and velocity, while utilising the same amount of reef material, making it an encouraging option for sustainable development.
5 Conclusions

In conclusion, this study has presented a numerical investigation of the wave transmission through artificial reefs used as low-crested breakwaters. The effectiveness of the shifted reef configuration in reducing wave energy has been evaluated using an SPH solver, specifically the DualSPHysics code. The wave transmission coefficients were calculated for different wave conditions and reef configurations. The results show that the shifted reef configuration provides a higher reduction level for non-breaking waves, but no significant difference in wave height reduction for breaking waves behind the breakwater. Furthermore, the efficiency of the breakwater decreases as the wave steepness increases. However, the total wave energy did significantly decrease, hence the wave height will gradually decrease as it travels further away behind the breakwater.

Overall, the artificial reef does reduce the wave height and velocity, with the shifted reef configuration giving better results in reducing the wave height and velocity with the same amount of reef material. However, its effectiveness still needs to be tested with various wave conditions. The present study is important for the design and optimization of artificial reefs as coastal protection structures, particularly in developing sustainable solutions for coastal erosion. It is recommended to conduct further studies to explore different configurations of artificial reefs and assess their performance under different wave conditions. The numerical simulations, coupled with experimental data, could provide more insights into the behaviour of artificial reefs as coastal protection structures.

References


10. Kraaijenest, File:Water wave theories.svg (This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license, 2009) https://commons.wikimedia.org/wiki/File:Water_wave_theories.svg