Physical and Numerical Simulation of Wave Transmission Over Submerged Breakwater

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Abstract. Nowadays, the submerged breakwaters are becoming attractive to the coastal engineer because they have many advantages including keeping aesthetic value of coastal scenery and reasonable for wave energy reduction. However, on the other hand, their design is very complicated. So, it is very important to understand the characteristics and the impact of wave because of the submerged breakwaters. For this purpose, we developed both numerical and physical model for simulation of wave over submerged breakwaters. The numerical model was developed using CADMAS-SURF, which is widely used in a practice of business in Japan. Physical model studies were performed at the Coastal Engineering Research Laboratory, University of Miyazaki, Japan to assess the performance of submerged breakwaters under a wide range of design conditions. The tests include the use of single and double submerged breakwater, as well as the impact of interval between the breakwaters which will be useful references for submerged breakwater designing in the future. The results show that the transmission coefficients of the numerical simulation have a good agreement with the experiment result with the RMS error 0.14 and 0.19 for the single and double breakwater respectively. This study found that, the application of double breakwaters has no significant impact for reducing wave energy compared to the single breakwater for the wave steepness higher than 0.007 and 0.012 based on laboratory and numerical simulation respectively. The best relative breakwater spacings are 0.75, 0.4, 0.45 and 0.35 for any kind of wave with the period of 0.6, 0.8, 1.0 and 1.2 respectively. In those conditions, the transmission coefficients are on minimum value for each kind of wave, that means the double breakwaters have the good performance on energy reduction.

1. Introduction
Nowadays, the submerged breakwaters are becoming more popular as an alternative for coastal protection measure where the transmission wave height and energy are acceptable. The submerged breakwaters are becoming attractive to the coastal engineer because they have many advantages including keeping aesthetic value of coastal scenery and reasonable for wave energy reduction (Makris et al. 2007, Makris and Memos 2007, Ranasinghe 2018). A successful design of submerged breakwaters may also cause beach restoration by trapping natural sediments. Submerged breakwaters are designed to reduce the incident wave energy in order to protect the coasts against erosion and port channels from sand deposition. Lower construction cost compared with other kinds of detached
breakwaters is another advantage. The advantages of submerged breakwaters over conventional structures make them more attractive for protecting natural and developed beaches. However, on the other hand, their design is very complicated. So, it is very important to understand the characteristics and the impact of wave transmission because of the submerged breakwaters. For this purpose, we developed both numerical and physical model for simulation of wave over submerged breakwaters.

In the present work, the numerical model was developed using CADMAS-SURF, which is widely used in a practice of business in Japan (Uemura 2014). The numerical results were compared with the results of the physical model. Physical model studies were performed at the Coastal Engineering Research Laboratory, University of Miyazaki, Japan (FIGURE 1) to assess the performance of submerged breakwaters under a wide range of design conditions. A key factor measuring the performance of the submerged breakwaters is the transmission coefficient $K_t$, i.e. the ratio of the transmitted to the incident wave height. The wave transmission coefficient increases with submergence depth (Mai 2001) and wave period and decreases with raising the incident wave height and the breakwater crest width (Teh and Hashim 2014). However, the present work focuses on studying the influences of applications single and double submerged breakwater, as well as the spacing between breakwater, which will be useful references for submerged breakwater designing in the future.

Figure 1. The flume for experiment in Coastal Engineering Research Laboratory, University of Miyazaki, Japan

2. Methods

Numerical Model
In this research, the numerical model was developed using CADMAS-SURF, which is widely used in a practice of business in Japan. CADMAS-SURF, introduced by Coastal Development Institute of Technology, Japan, 2001, has been adopted into the numerical model in this research due to the following functions (Uemura 2014): capable of simulating complex free surfaces, high accuracy for describing an obstacle by means of the porous model, capable of locating obstacles/boundaries conditions at any position, several wave-making sources, and capable of dealing with bubble contamination as well as water residue. The CADMAS-SURF has been widely used for wave simulation for any kind or purposes (Wijatmiko and Murakami 2010, Wijatmiko and Murakami 2012, Usman et al. 2016, Usman et al. 2014, Mubarak et al. 2019). The basic equations in this direct numerical simulation are the continuity equation and momentum equation, known as the Navier-Stokes equations. This study employs a system of such equations, discretized with the finite difference method to simulate wave propagation at the coastal zone. The governing equations consisted of a continuity equation, Navier-Stokes equation in x and z-direction and an advection equation for tracing the temporal water surface elevation, as shown in Eq (1)-(4). The last equation includes the function, $F(x,z,t)$, which means the ratio of water volume in each numerical cell.
\[
\frac{\partial \gamma_x u}{\partial x} + \frac{\partial \gamma_z w}{\partial z} = S_p
\]  
\[\lambda_v \frac{\partial u}{\partial t} + \frac{\partial \lambda_x u u}{\partial x} + \frac{\partial \lambda_z w u}{\partial z} = -\frac{\gamma_v}{\rho} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \gamma_x v_e \left( 2 \frac{\partial u}{\partial x} \right) \right) + \frac{\partial}{\partial z} \left( \gamma_z v_e \left( 2 \frac{\partial w}{\partial z} \right) \right) - D_x u + S_u - R_x
\]  
\[\lambda_v \frac{\partial w}{\partial t} + \frac{\partial \lambda_x u w}{\partial x} + \frac{\partial \lambda_z w w}{\partial z} = -\frac{\gamma_v}{\rho} \frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \left( \gamma_z v_e \left( 2 \frac{\partial w}{\partial z} \right) \right) - D_z w + S_w + S_u - R_x - \gamma_v g
\]  
\[\gamma_v \frac{\partial F}{\partial t} + \frac{\partial \gamma_x u F}{\partial x} + \frac{\partial \gamma_z w F}{\partial z} = S_F
\]

where, \(t\) means the time, \(x\) and \(z\) mean the horizontal and vertical coordinate. Also, \(p\) means the pressure, \(u\) and \(w\) mean the horizontal and vertical velocity components, respectively. \(\rho\) is the density of the fluid, \(v\) is the summation of molecular kinematic viscosity and eddy kinematic viscosity, \(g\) is the gravity acceleration. \(\gamma_v\) is the volume porosity, \(\gamma_x\) and \(\gamma_z\) are the aerial of porosity components, \(S_F\), \(S_u\), and \(S_w\) are wave generation source, \(D_x\) and \(D_z\) are the coefficients for sponge layer, and \(R_x\) and \(R_z\) are the resistant components due to porosity in \(x\) and \(z\)-axis.

Physical and Numerical Simulation

Physical and numerical simulations were conducted in the same model size and condition, as presented in FIGURE 2 and TABLE 1. A series of laboratory experiments was conducted in the wave-current flume (15.0 m long, 0.4 m wide and 0.6 m depth) at the University of Miyazaki to obtain data to investigate the predictive skills of the numerical models. The experiments were simulated on three scenarios, such as without breakwater, with single submerged breakwater and with double submerged breakwaters. The submerged breakwater models were made of solid impermeable blocks that were placed 8.0 m from the wave generator. The model was set to 0.4 m water depth, 0.34 m submerged breakwater height, and 0.5 m distance between two breakwaters. The simulations were carried out on 10 times wave period, i.e. 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2 and 2.4 seconds. We measured the wave height at 2 m distance from upstream \((H_u)\) and downstream \((H_d)\) of breakwater. Numerical simulations have been carried out with the same scenario as the above physical model simulation and with additional simulations for various interval between the two breakwaters in order to understand the effect on wave energy dissipation. The simulations were carried out for the same wave periods above for each of interval between submerged breakwaters, i.e. 0.3\(H_b\), \(H_b\), 2\(H_b\), 3\(H_b\) and 4\(H_b\), where \(H_b\) is the height of submerged breakwater.
Figure 2. Layout of the experimental setup and computational domain for without breakwater (a), single breakwater (b), and double breakwater (c)

Table 1. Simulation scenarios for physical and numerical simulation

| Simulation model       | Period (second) |
|------------------------|-----------------|
|                        | 0.6  | 0.8  | 1.0  | 1.2  | 1.4  | 1.6  | 1.8  | 2.0  | 2.2  | 2.4  |
| without Breakwater     | A_1  | A_2  | A_3  | A_4  | A_5  | A_6  | A_7  | A_8  | A_9  | A_10 |
| Single Breakwater      | B_1  | B_2  | B_3  | B_4  | B_5  | B_6  | B_7  | B_8  | B_9  | B_10 |
| Double Breakwaters     | C_1  | C_2  | C_3  | C_4  | C_5  | C_6  | C_7  | C_8  | C_9  | C_10 |
| 0.3 H_b                | D_1  | D_2  | D_3  | D_4  | D_5  | D_6  | D_7  | D_8  | D_9  | D_10 |
| H_b                    | E_1  | E_2  | E_3  | E_4  | E_5  | E_6  | E_7  | E_8  | E_9  | E_10 |
| 2 H_b                  | F_1  | F_2  | F_3  | F_4  | F_5  | F_6  | F_7  | F_8  | F_9  | F_10 |
| 3 H_b                  | G_1  | G_2  | G_3  | G_4  | G_5  | G_6  | G_7  | G_8  | G_9  | G_10 |
| 4 H_b                  |      |      |      |      |      |      |      |      |      |      |

3. Results and Discussion
To analyze the performance of the submerged breakwater to reduce the energy wave, we calculated the transmission coefficient which was defined as the ratio between measures of the transmitted ($H_t$) and incident waves ($H_i$). The transmission coefficient illustrates how well the breakwater in reducing wave height, the smaller the value of the transmission coefficient the better the breakwater in reducing wave height. The transmission coefficients were analyzed on both single and double breakwaters by physical model and numerical simulation. FIGURE 3(a) and FIGURE 3(b) presented the correlation between the transmission coefficient and the wave steepness ($H_o/gT^2$) for single breakwater and for double breakwaters respectively as the result of laboratory experiments and numerical simulations. The wave steepness is defined as the characteristic of individual waves calculated as wave height divided by wavelength. The Figures show that in case of single breakwater, the transmission coefficients from experiment tend to be higher than that of from numerical simulation. However, in the case of double breakwaters, the transmission coefficients from experiment were higher than that of from numerical simulation only for the wave steepness $\geq 0.005$. For the wave steepness $\leq 0.005$, the transmission coefficients from numerical simulation were higher than that of from experiment. The root mean square error (RMS) for the transmission coefficients of the numerical simulation to experiment are 0.14 and 0.19 for the single and double submerged breakwater respectively.
Figure 3. The numerical simulation and laboratory experiment of transmission coefficient and wave steepness for single breakwater (a) and double breakwaters (b)

Figure 4 shows the impact of single and double submerged breakwaters on transmission coefficient based on the wave steepness from laboratory experiment (a) and from numerical simulation (b). Based on laboratory experiment, the transmission coefficients were reduced significantly by applying the double submerged breakwaters especially for wave steepness less than 0.007, as presented in FIGURE 4(a). It means that, for the wave steepness higher than 0.007, the application of double breakwaters has no significant impact for reducing wave energy compared to the single breakwater. Also, based on the numerical simulation, the application of those breakwater has the similar impact. The transmission coefficients were reduced by applying the double submerged breakwaters for wave steepness less than 0.012, as presented in figure 4(b). This means that, the greater the value of wave steepness, the smaller the influence of the use of double breakwater in terms of reducing wave energy compared to the use of a single breakwater.

Figure 4. The impact of single and double submerged breakwaters on transmission coefficient and wave steepness based on laboratory experiment (a) and numerical simulation (b)

Effect of relative breakwater spacing S/Lo
The following section investigates the effect of relative breakwater spacing S/Lo on wave propagation based on numerical simulations. It aims to find the most appropriate breakwater spacing S/Lo as references for the practical engineering. FIGURE 5 shows the curves of transmission coefficient (Kt) against relative breakwater spacing S/Lo, for regular waves of various period (a), and for various breakwaters interval. From FIGURE 5a, the transmission coefficients have no change for the relative breakwater spacing S/Lo ≥ 1.2 with any kind of wave period. It means that the application of double breakwaters will not effective if the relative breakwater spacing higher than 1.2. How is the best relative breakwater spacing for double breakwater depends on each characteristic of wave period. The best relative breakwater spacing is 0.75, 0.4, 0.45 and 0.35 for any kind of wave with the period of 0.6,
0.8, 1.0 and 1.2 respectively. In those conditions, the transmission coefficients are on minimum value for each kind of wave. However, for any kind of breakwater interval, it is better to set the relative breakwater spacing less than 0.5. Thus, the transmission coefficients are lower than the other conditions, that means the double breakwaters have the good performance on energy reduction. For the reference, Liang et al. (2015) confirmed that the value of appropriate relative breakwater spacing S/Lo was around 1.11, provided the relative submerged depth R/H is fixed to 1.0.

![Figure 5.](image)

**Figure 5.** The transmission coefficient ($K_t$) against relative breakwater spacing S/Lo, for regular waves of various period (a), and for various interval between breakwaters.

### 4. Conclusions

This study analyzed the wave transmission over submerged breakwater by using physical and numerical simulation. The numerical model was developed using CADMAS-SURF and the physical model was performed at the Coastal Engineering Research Laboratory, University of Miyazaki, Japan to assess the performance of submerged breakwaters under a wide range of design conditions. The tests include the use of single and double submerged breakwater, as well as the impact of interval between the breakwaters which will be useful references for submerged breakwater designing in the future. The results show the transmission coefficients of the numerical simulation have a good agreement with the experiment result with the RMS error 0.14 and 0.19 for the single and double submerged breakwater respectively.

This study found that, the greater value of wave steepness, the smaller influence of the use of double breakwater in terms of reducing wave energy compared to the use of a single breakwater. Application of double breakwaters has no significant impact for reducing wave energy compared to the single breakwater for the wave steepness higher than 0.007 and 0.012 based on laboratory and numerical simulation respectively. This study also found that, the best relative breakwater spacings are 0.75, 0.4, 0.45 and 0.35 for any kind of wave with the period of 0.6, 0.8, 1.0 and 1.2 respectively. In those conditions, the transmission coefficients are on minimum value for each kind of wave, that means the double breakwaters have the good performance on energy reduction.

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**References**

[1] Liang B, Wu G, Liu F, et al 2015 Numerical study of wave transmission over double submerged breakwaters using non-hydrostatic wavemodel *Oceanologia* 57 308–317

[2] Mai S 2001 Wave Transmission at Submerged Breakwaters *In: Proc. of the 4th Int. Symposium on Ocean Wave Measurement and Analysis* p 10

[3] Makris C V, Avgeris I, Memos CD 2007 Hydraulic Behaviour of Submerged Breakwaters *In: 4th International Conference Port Development and Coastal Environment* p 10
[4] Makris C V, Memos CD 2007 Wave Transmission over Submerged Breakwaters: Performance of Formulae and Models Wave Transmission over Submerged Breakwaters: Performance of Formulae and Models *In: Proceedings of the Sixteenth (2007) International Offshore and Polar Engineering Conference* p 9

[5] Mubarak M, Sutikno S, Defarian A, et al 2019 Numerical simulation of detached breakwaters for mangrove restoration in Bengkalis Island, Indonesia *In: MATEC Web of Conferences ICAnCEE 2018* pp 1–8

[6] Ranasinghe R S 2018 Numerical modelling of wave transformation over submerged breakwaters using Boussinesq-type models Numerical modelling of wave transformation over submerged breakwaters using Boussinesq-type models *J Natl Sci Found Sri Lanka* 3 369–379

[7] Teh H M and Hashim A M 2014 Submerged modular breakwaters for coastal protection *Adv Fluid Mech* 82 121–130

[8] Uemura T 2014 A numerical simulation of the shape of submerged breakwater to minimize mean water level rise and wave transmission

[9] Usman F, Murakami K, Kurniawan E B 2014 Study on Reducing Tsunami Inundation Energy by the Modification of Topography based on Local Wisdom *Procedia Environ Sci* 20 642–650

[10] Usman F, Wicaksono A D and Setiawan E 2016 Evaluation of the Reduction of Tsunami Damages Based on Local Wisdom Countermeasures in Indonesia *Rev Eur Stud* 8 157–165

[11] Wijatmiko I and Murakami K 2012 Study on the Interaction Between Tsunami Bore and Cylindrical Structure with Weir *Hydrodyn - Theory Model* 58–78

[12] Wijatmiko I and Murakami K 2010 Three Dimensional Numerical Simulation of Bore type Tsunami Propagation and Run-up on to a Dike *J Hydrodyn* 22 259–264