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# Study on wave prevention efficiency of submerged breakwater using an advanced mathematical model

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**Abstract.** The paper presents the results of a numerical study on the interaction of waves and a submerged breakwater. The numerical study is the application of an advanced numerical model named as CMED, which is based on the Narvier-Stokes equations and VOF (Volume of Fluid) method, and has been previously developed by the author. The consideration is paid for the investigation on the influence of the characteristics of the breakwater on the variation of some parameter coefficients, such as reflection, transmission and energy dissipation coefficients. Based on the systematic analysis of the numerical results, the wave prevention efficiency of the breakwater is discussed. The results show that there are an effective range of the water depth at the top of the submerged breakwater and an effective range of the breakwater width in relation to the incident wave length that produces the effective performance of the submerged breakwater regarding to the wave prevention efficiency. The results of this study also confirm that the energy dissipation due to wave breaking processes is one of key issues in the practical design of an effective breakwater.

*Keyword:* Submerged breakwater; Wave transmission; Wave prevention; Numerical experiment.

## 1. Introduction

Understanding the interaction of waves and coastal structures in general and the interaction of waves and submerged breakwaters in particular, is difficult but very useful in practice for design of effective breakwaters to protect coastal areas from storm wave attacks. Hydrodynamic processes in the coastal region are very important factors for coastal engineering design, in which the water wave propagation and its effects on coasts and on the coastal structures are extremely important. The interactions between waves and a coasta structure are highly nonlinear and complicated They involve the wave shoaling, wav breaking, wave reflection, turbulence an possibly wind-effects on the water spray. Th appearance of a coastal structure, for example breakwater, can alter the wave kinematics an may result in very complicated processes suc as the wave breaking, wave overtopping and th wave force acting on the structure. Therefore before a prototype is built in the field, normall engineers need to carry out a number o physical modeling experiments to understan the physical mechanisms and to get an effectiv design for the prototype. This task give specific difficulties sometime, and the cost o

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periments is an issue. One of the main oblems in small-scale experiments is that ffects of the small scale may cause iscrepancies to the real results. To minimize e scale effects, in many developed countries, r example, US, Japan, Germany, England, etc, ngineers build large-scale wave flumes to tudy the characteristics of prototype in the early real scale or real scale. These can reduce r even avoid the scale effects. However, there re still some remaining problems, such as high onsumption costs and undesirable effects of hort wave and long wave reflections. herefore, the contamination of the action of ong waves in experimental results is still nevitable.

Recently, some numerical studies based on he VOF-based two-phase flow model for the imulation of water wave motions have been eported. Hieu and Tanimoto (2002) developed VOF-based two-phase flow model to study wave transmission over a submerged obstacle [1]. Karim et al. (2003) [5] developed a VOF-based two-phase flow model for wave interactions with porous structures and studied the hydraulic performance of a rectangle porous structure against non-breaking waves. Their numerical results surely showed a good agreement with experimental data. Especially, Hieu et al. (2004) [2] and Hieu and Tanimoto (2006) [4] proposed an excellent model named CMED (Coastal Model for Engineering Design) based on the Navier-Stokes equations and VOF method for simulation of waves in surf zone and wave-structure interaction. Those studies have provided with useful tools for consideration of numerical experiments of wave dynamics including wave breaking and overtopping.

In this study, we apply the CMED model to study the interaction of waves and a submerged breakwater and to consider the wave prevention efficiency of the submerged breakwater. The study is focused on the influence of submerged breakwater height and width on the transmission of waves.

## 2. Model description

In the CMED model (Hieu and Tanimoto, 2006) [4], the governing equations are based on the Navier-Stokes equations extended to porous media given by Sakakiyama and Kajima (1992) [6]. The continuity equation is employed for incompressible fluid. At the nonlinear free surface boundary, the VOF method [3] is used. The governing equations are discretized by using the finite difference method on a staggered mesh and solved using the SMAC method. Verification of the CMED model has been done and published in an article on the International Journal of Ocean Engineering. The proposed results revealed that the CMED model can be used for applied studies and be a useful tool for numerical experiments (for more detail see [4]).

## 3. Wave and submerged breakwater interaction

### 3.1. Experiment setup

Study of wave and submerged breakwater is carried out numerically. In the experiment, a submerged breakwater with the shape of trapezium having a slope of 1/1.3 at both foreside and rear side, is set on a horizontal bottom of a numerical wave tank. The water depth in the tank is constant equal to 0.375m. The incident waves have the height and period equal to 0.1m and 1.6s, respectively. The breakwater is kept to be the same sharp while the height and width of the breakwater are variable.

First, experiment is done with varying heights of breakwater in order to investigate the variation of wave height distribution and reflection, transmission and dissipation coefficients versus the variation of water depth at the top of the breakwater. For this purpose, the breakwater height is changed so as the water depth at the top is varying from 0 to 0.375m. Second, after the first experiment, the next investigation is carried out using some selected water depths at the top of the breakwater and a set of breakwater widths varying from 0.1 to 1.1 times incident wave length. This experiment is to get the influence of the breakwater width on the wave prevention efficiency of the breakwater. Fig. 1 presents the sketch of the experiment.

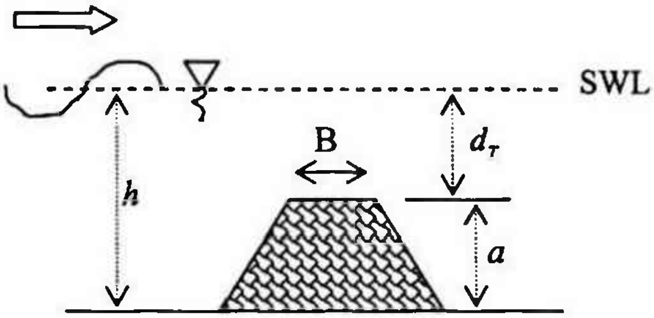

Fig. 1. Description of experiment.

### 3.2. Results and discussion

The first numerical experiment is to investigate the influence of the height of the breakwater on the transmission waves and reflection effects. The numerical results are shown in the Fig. 2. The notations $K_T$, $K_R$, $K_d$ are used for the transmission, reflection and energy dissipation coefficients. From this figure, it is seen that the reflection coefficient $K_R$ gradually decreases versus the increase of the normalized depth at the top of the breakwater, or versus the decrease of the breakwater height. The quantity $d_T$ denotes the water depth at the top of the breakwater. The ratio $d_T / H_I$ (where $H_I$ is the incident wave height) equal to zero means that the height of the breakwater is equal to the water depth $h$.

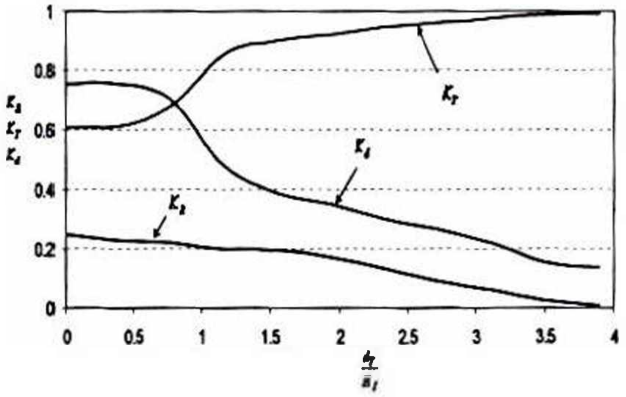

Fig. 2. Variation of reflection, transmission and dissipation coefficient versus water depth at the top of the breakwater.

For the transmission and dissipation coefficients, the variation is very different. The transmission and dissipation coefficients respectively decrease and increase when the height of the breakwater increases (or when the water depth at the top of the breakwater decreases). Especially, when the water depth at the top of the breakwater decreases to approximately 1.2, there is an abrupt change of the transmission as well as dissipation coefficients, and this change keeps up to the value of $d_T / H_I$=0.6. After that, the decrease of $d_T / H_I$ results in not much variation of $K_T$ and $K_d$. This can be explained that due to the presence of wave breaking process as the water depth at the top of the breakwater less than the incident wave height ($d_T / H_I$<1), the wave energy is strongly dissipated and results in the significant change of the dissipation coefficient, and consequently results in the change of the transmission coefficient. When $d_T$ decreases more, $K_d$ also increases, however, there is a limited value of $d_T / H_I$ (the value is approximately equal to 0.6 in Fig. 2), the more reduction of $d_T$ does not give a significant change of $K_d$. This can be explained that this value of $d_T / H_I$ is enough to force the wave to break fully, and most wave energy is dissipated due to this forcing. Therefore, more reduction of $d_T$ could not give more significant energy dissipation. This suggests that there is an effective range of water depth at the top of submerged breakwater that can give a good performance of the breakwater in prevention of waves.

From the results of the first experiment, there is a question: is there any effective range of the width of the breakwater regarding to the wave prevention? To answer this question, the second experiment is considered with three values of $d_T / H_I$ equal to 0.6, 0.8 and 1.0. Thus, there are three sets of experiments. In each set, the change of breakwater width $B$ is considered with the ratio $B / L$ in the range from 0.1 to 1.1, in which $L$ is the wave length.

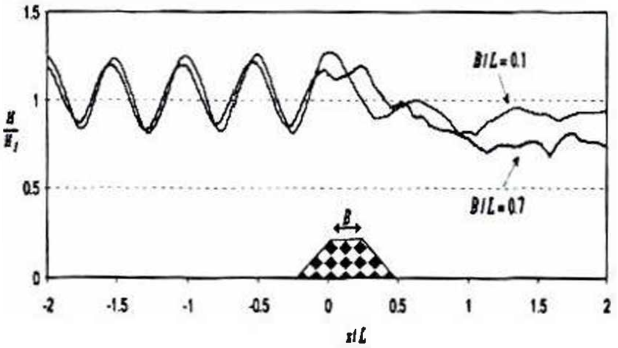

Fig. 3. Wave height distribution a long the breakwater in the case of $\frac{d_T}{H_I} = 1.0$.

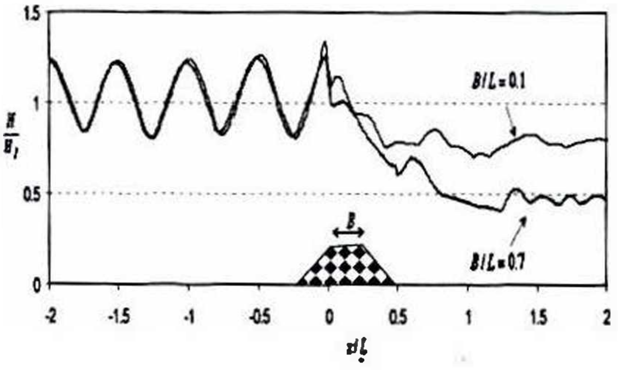

Fig. 4. Wave height distribution along the breakwater in the case of $\frac{d_T}{H_I} = 0.6$.

Fig. 3 shows the distribution of wave height around the breakwater for the case of $d_T / H_I$=1.0. There are two lines presenting the wave height distribution for two cases $B / L$=0.1 and $B / L$=0.7. At the foreside of the breakwater (left side of the figure), it is the presence of the partial standing waves due to the combination of the incident and reflected waves. At the rear side of the breakwater, the wave height is smaller than that of the incident wave due to the reflection at the fore side and the wave energy dissipation at the breakwater. We can see that the wider breakwater gives smaller transmitted waves at the rear side. From the figure, it is also seen that the wave breaking is not so strong. In Fig. 4, the distribution of wave height is somewhat similar to that in Fig. 3; however, the wave breaking in Fig.4 is much stronger. The transmitted wave height is about 0.7 times the incident wave height for the case $B / L$=0.1 and comparable to the case $B / L$=0.7 in Fig. 3. With the case $B / L$=0.7 in Fig. 4, the transmitted wave height is only $0.5 H_I$. The wave height difference between the cases $B / L$=0.1 and $B / L$=0.7 is about 0.25 in $K_T$. This means that approximately 6.25% of wave energy has been dissipated due to different types of wave breaking. Therefore, the wave energy dissipation due to breaking processes should be considered in practical design of effective breakwaters.

Fig. 5 presents the time variation of total wave energy, which is normalized by the incident wave energy, at the rear side of the breakwater. In this figure, $t$ is the time and $T$ is the wave period. We can see that after four wave periods, the transmitted wave comes to the observed location. The wave energy is exponentially increasing during duration of approximately 4 times the wave period $T$. After that, the wave energy becomes stable and approaches a constant value. It is clearly seen that when the ratio $B / L$ is small, the change of wave energy versus the variation of $B / L$ is fast; this is presented in the figure by the big distance between two adjacent lines. When $B / L$ is greater than 0.6, the distance between two adjacent lines becomes smaller and the change of wave energy is slow down versus the change of the ratio $B / L$. The same aspect can be seen in the Fig. 6 by the presentation of variation of three quantities, the reflection, transmission and dissipation coefficients, versus the change of the breakwater width. It is worthy to note that the dissipation coefficient is calculated using the formula $K_d = \sqrt{1-K_R^2-K_T^2}$ .

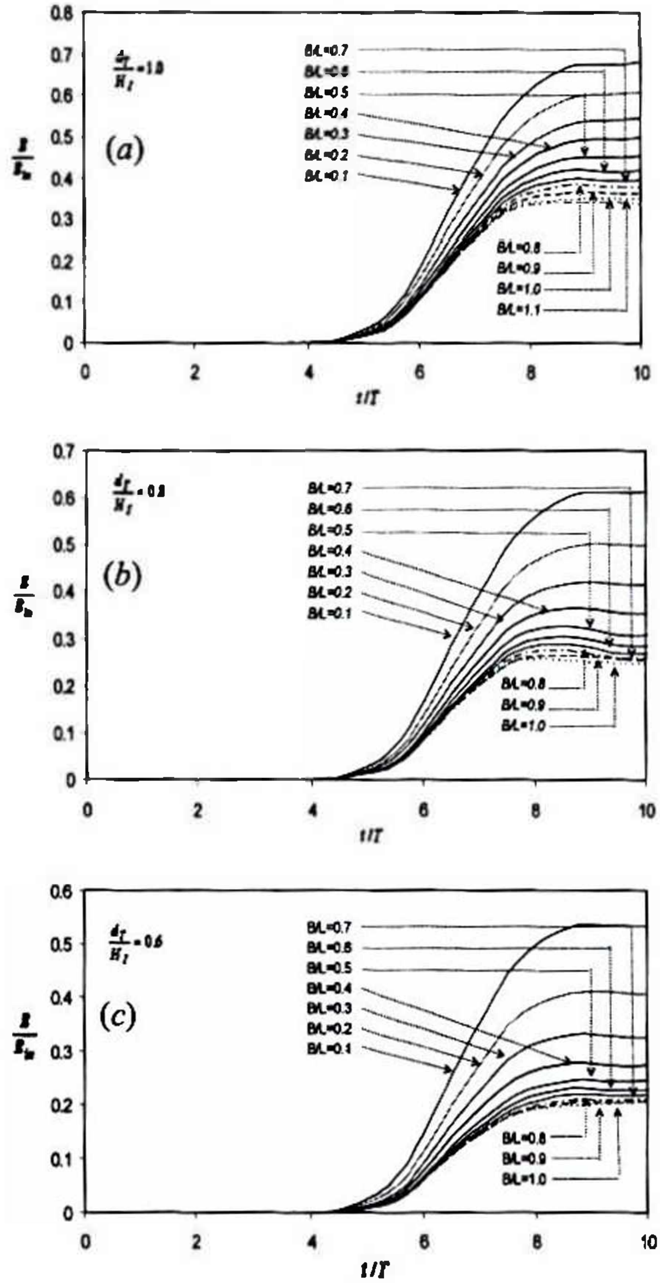

Fig. 5. Time variation of normalized total wave energy behind the breakwater $(a)\ \frac{d_T}{H_I}=1.0$; $(b)\ \frac{d_T}{H_I}=0.8$; $(c)\ \frac{d_T}{H_I}=0.6$.

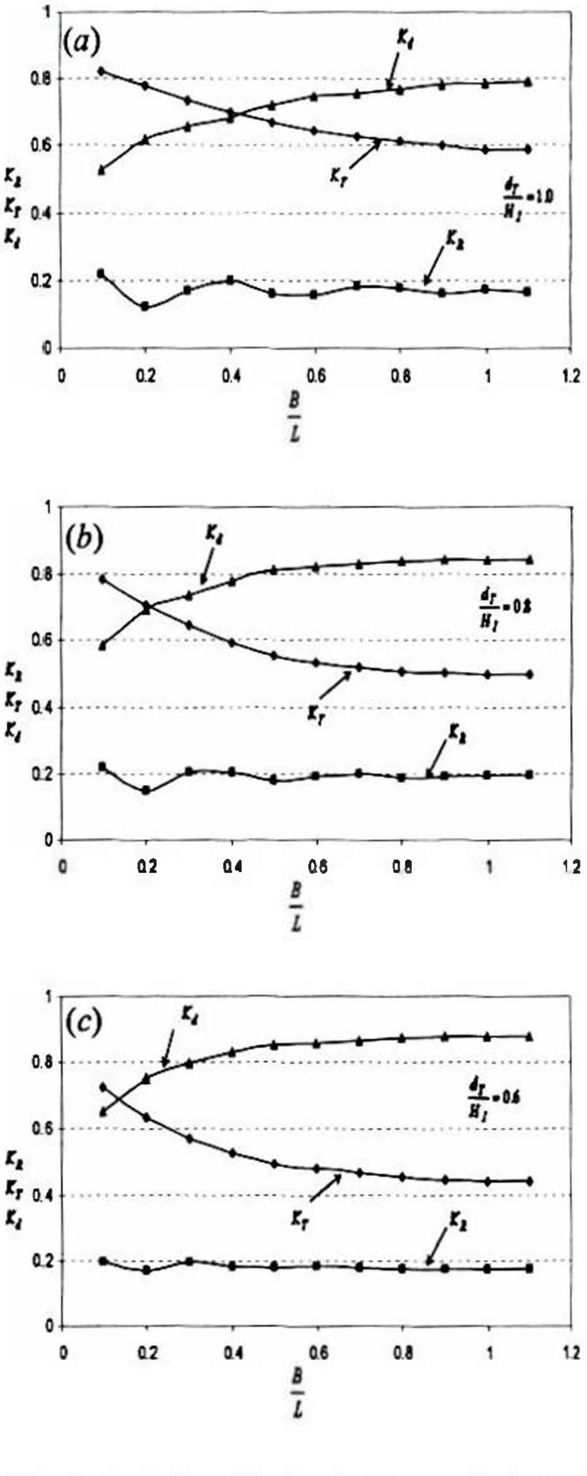

Fig. 6. Variation of reflection, transmission and energy dissipation versus breakwater width $(a)\ \frac{d_T}{H_I}=1.0$; $(b)\ \frac{d_T}{H_I}=0.8$; $(c)\ \frac{d_T}{H_I}=0.6$.

In Fig. 6, the reflection coefficient $K_R$ varies in a complicated manner versus the change of $B/L$. At first, the coefficient $K_R$ is fluctuated and then it becomes more stable when the width $B/L$ increases. The reflection coefficients $K_R$ in three cases (Fig. 6a, b, c) are all less than 0.2 and not so much different among them. This means that the height of the breakwater $a$ greater than $h-H_I$ (or $\frac{d_T}{H_I}<1.0$) can gives not much change in the reflection function of the breakwater. The transmission coefficient $K_T$ decreases gradually versus the increase of $B/L$.

There is a variation range of $B/L$, in which the change of $K_T$ is very fast, minus steep slope of $K_T$ can be clearly observed from all cases ((*a*) $\frac{d_T}{H_I}=1.0$; (*b*) $\frac{d_T}{H_I}=0.8$; (*c*) $\frac{d_T}{H_I}=0.6$). The increase of $B/L$ comes to a specific value, after that the increase more of $B/L$ can not result in a significant decrease of $K_T$. The specific value is changeable from case to case. We can see in Fig. 6 that for the case $\frac{d_T}{H_I}=1.0$, the specific value of $B/L$ is roughly 0.7; for the case $\frac{d_T}{H_I}=0.8$ and $\frac{d_T}{H_I}=0.6$, it is 0.6. These specific values can be considered as the effective values of the width of the breakwater, because if the breakwater is built up with the bigger value of $B/L$, the decrease of $K_T$ is not much. This means that the transmitted wave height behind the breakwater reduces not significantly, therefore consumption cost for the material (for example, to build the wider breakwater) is not so effective. It is also seen from the figure that for the higher breakwater, we get the smaller effective value of $B/L$. The dissipation coefficient in Fig. 6 varies in the same manner as the transmission coefficient but inversely. At first, when the value $B/L$ increases, the coefficient $K_d$ increases fast, after that, its change is slow down and $K_d$ approaches a constant value when the ratio $B/L$ reaches the effective value. The coefficient $K_d$ represents the energy lost due to the shallow effects (such as friction, wave breaking, turbulence etc.), thus, the bigger value of $K_d$ means lager wave energy dissipation. From Fig. 6c, if we consider value of $B/L$=0.5, we can see that 50% of wave height is reduced when the incident wave is passing over the breakwater, and the value of $K_d$=0.85 gives us the information that about 72% of wave energy (equal to $(K_d)^2$) is dissipated at the breakwater. Where as there is only about less than 4% of wave energy (equal to $(K_R)^2$) is stopped and reflected by the breakwater. Therefore, the wave energy dissipation due to breaking should be considered as the key issue to design an effective wave prevention breakwater in practice.

## 4. Conclusions

In this study, numerical experiments for the interaction of waves and submerged breakwater have been investigated using the advanced Navier-Stokes VOF-based model CMED. The first experiment was carried out for nine cases of variation of the breakwater height to investigate the influence of the water depth at the top of the submerged breakwater on the wave prevention function of the breakwater. The second experiment was done for 33 cases of variation of the width of the breakwater in the combination with three selected breakwater heights in order to study the effect of dimensionless breakwater width on the wave reflection, transmission and dissipation processes. The results show that there is an effective range of the submerged breakwater related to the incident wave length that makes the performance of the submerged breakwater be effective in preventing the incident waves. The effective value of the water depth at the top of the submerged breakwater is within the range from 1.0 to 0.6 times the incident wave height, and the effective value of the breakwater width is in the range from 0.5 to 0.7 times the incident wave length.

The results of this research also show that in the case of the selected breakwater, the maximum reflection effect can give only 4% of wave energy to be reflected; where as almost 70% of the incident wave energy can be dissipated at the breakwater. Those results suggest that the energy lost due to wave breaking processes is the key issue and should be considered carefully in the practical design to get an effective submerged breakwater regarding to the wave prevention efficiency.

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