WAVE REDUCTION ABILITY PASSING OVER SUBMERGED BREAKWATER USING POROUS CONCRETE BY FLOW-3D SOFTWARE

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Abstract

This paper presents the results of a study on the wave height reduction efficiency of submerged breakwaters constructed from porous concrete structures (PCSB), using FLOW-3D software. The simulations were conducted on a model with dimensions of 45 m (length) × 1.0 m (width) × 1.5 m (height) and included four groups of scenarios: variations in porosity, the freeboard to incident wave height ratio (S/H), the crest width to wave length ratio (B/L), and the slope of the structure. The simulation results were calibrated against experimental data from different cross-sections, demonstrating strong compatibility. This study clarifies the mechanisms of wave propagation and absorption as they pass over PCSB. When properly designed, the wave reduction efficiency of PCSB is quantified by the coefficient of transmitted wave height to incident wave height, illustrating the practical applicability of these structures. The FLOW-3D software employed in this research serves as an effective tool for analyzing wave deformation over PCSB, significantly contributing to the design of these structures as effective coastal protection measures.

Keywords: *Porous concrete; wave reduction; submerged breakwater; FLOW-3D software.*

1. Introduction

Global climate change is expected to affect tropical storms with more frequency and intensity. Therefore, it is clear that research on coastal protection solutions has gained more popularity. In particular, submerged breakwaters play a pivotal role to protect the coast from erosion under the extreme effects of weather conditions such as waves, wind, rising sea level and currents. According to statistics up to 2005, Europe has more than 1,200 submerged breakwaters, accounting for more than 60% of the total number of breakwaters [1]-[3]. Submerged breakwaters have the effect of dissipating part of the wave energy when transmitted passing over the submerged breakwater and decreasing the incident wave height (Fig. 1). It leads to a reduction in flow velocity and improves the ability to deposit sand and mud at the shoreline without disrupting existing coastal cycles [4]. In addition, the outstanding advantage of submerged breakwater is that the structure has

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a low crest that does not interrupt the view, so it is definitely suitable for areas that require high aesthetics such as tourist beaches.

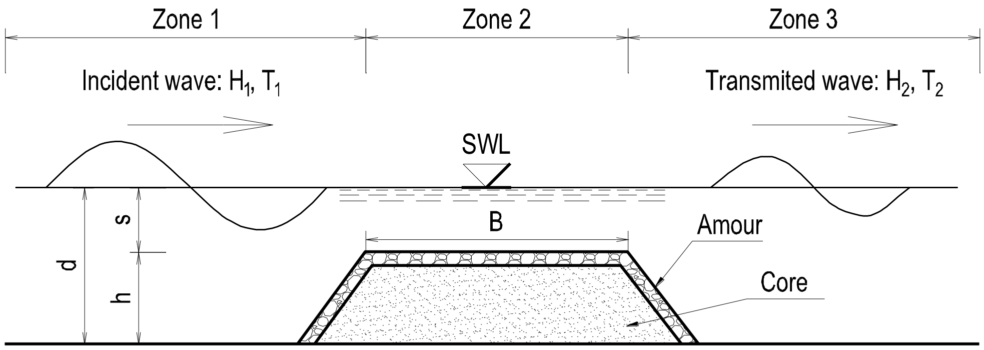


Fig. 1. Typical cross section of submerged breakwater.

In order to ensure their function, materials for making submerged breakwaters must survive in severe environments as: waves, wind, currents, storm surges. Furthermore, the breakwater's ability to withstand sediment abrasion, chemical attack, corrosion, and destruction by marine organisms [5]. There are many types of materials that have been applied to submerged breakwater: rubble, concrete, reinforced concrete, irregularly shaped blocks, wooden screen structures, geotube, porous concrete. Among these, porous concrete is concrete with an interconnected porous structure created from intermittent aggregate grain gradations. Porous concrete has the ability to absorb wave energy reaching the surface of the PCSB by partially dissipating it before and during interaction with the structure (Fig. 2), so it is considered as an active solution to protect the coast.

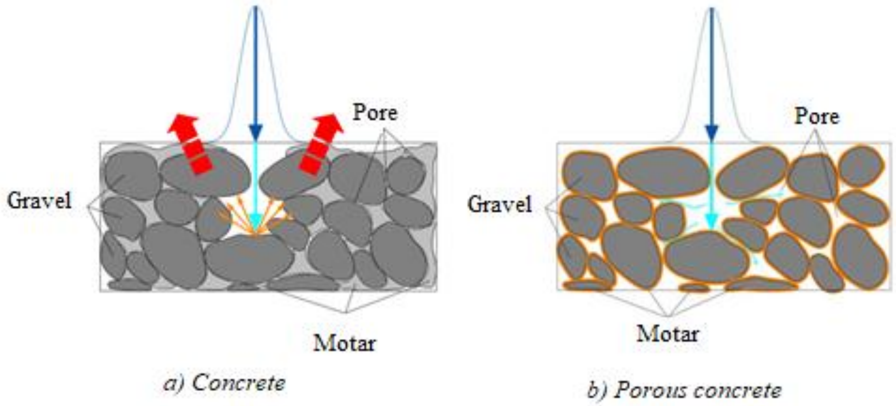


Fig. 2. Working mechanism of porous concrete block.

In worldwide, this material has been applied to a number of coastal protection works due to its capability to absorb wave energy actively (Fig. 3). In Vietnam, the use of this material is still limited, mainly in traffic works with drainage functions [2], no porous concrete structure has been applied to submerged breakwater works in practice. The main reason is that research on porous concrete is still limited and mainly in the laboratory, focusing on studying the physical and mechanical properties of the material. In particular, studies on wave - PCSB interaction have not been widely published, mainly based on experimental results in physical models. This method requires a lot of time, cost and is sometimes limited by experimental conditions [2], [6]. Therefore, to effectively apply this type of structure, specific and detailed studies are needed on many criteria, in which the important property is the wave reduction efficiency of PCSB.

Fig. 3. Application of porous concrete in revetment.

Therefore, in this study, the authors focus on another approach, which is to use the FLOW-3D software to simulate the operation of the PCSB. From there, the mechanism of wave absorption and transmission passing over this type of structure is clarified. The simulation results are verified with the physical experimental model, showing high suitability and accuracy, so this method is very suitable for research and practical applications.

2. Experimental investigation

The experimental work in this paper uses the research results of the ministerial-level project "Research on manufacturing porous concrete with wave reduction effect to protect island and coastal shores", published in the paper "Experimental assessment of wave reduction possibility of porous concrete blocks" [2] for the purpose of calibrating the FLOW-3D model. The detail of experimental setup is shown in Figs. 4, 5.

Four wave gause groups, WG1 through WG6, are set up at various locations. WG1 is used to measure the deep water wave; the incident and reflected waves are separated by WG2, WG3, WG4, and WG5; and WG6 is used to measure the transmitted wave after a wave passes over the sample block [2]. Regular waves with H = 0.1 m, T = 1.6 s, D = 0.75 m, and S = 0.05 m are utilized in experimental work.

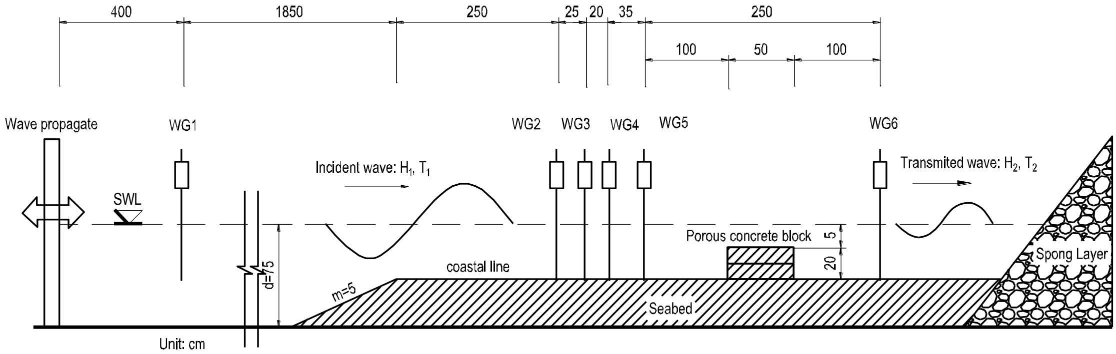


Fig. 4. Detail of the experimental setup.

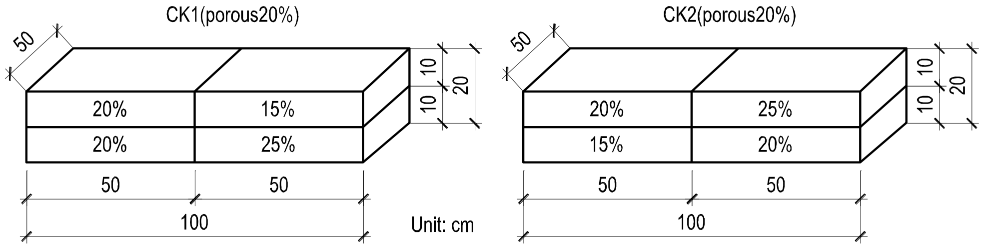


Fig. 5. Porous concrete blocks in detail.

3. Numerical model

FLOW-3D software is used as the research tool of the paper. FLOW-3D has been proven to be suitable in studying wave - structure interaction [7].

3.1. Governing equations

FLOW-3D uses the Navier-Stoker equation as the main equation, solved using the volume of fluid (VOF) technique. This equation is a combination of two conservation equations of mass and momentum, in the 3-dimensional Cartesian coordinate system (x, y, z). The continuous mass equation is represented by the following formula [8].

a) Continuity equation

The general form of the mass continuity equation is:

$$V_F\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}\left(\rho uA_x\right)+R\frac{\partial}{\partial y}\left(\rho vA_y\right)+\frac{\partial}{\partial z}\left(\rho wA_z\right)+\xi\frac{\rho uA_x}{x}=R_{\mathrm{DIF}}+R_{\mathrm{SOR}} \quad (1)$$

where V_F is the initial volume of the flow, ρ is the density of the flow, R is the coefficient related to the turbulent diffusion of the liquid, u, v, w are the velocity components of the fluid in the x, y, z directions; A_x, A_y, A_z are liquid element areas in the corresponding directions perpendicular to the x, y, z axes in the Cartesian coordinate system;

With approximation, the continuity equation is written in the following form:

$$\frac{V_F}{\rho c^2}\frac{\partial \rho}{\partial t}+\frac{\partial uA_x}{\partial x}+R\frac{\partial vA_y}{\partial y}+\frac{\partial \mathrm{w}A_z}{\partial z}+\xi\frac{uA_x}{x}=\frac{R_{\mathrm{SOR}}}{\rho} \tag{2}$$

b) Momentum equation

In the Cartesian coordinate system, the equation of motion of the fluid components (u, v, w) in three coordinate directions is the Navier-Stokes equation with some additional conditions expressed as follows [8]:

$$\begin{aligned}
&\frac{\partial u}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial x}+wA_z\frac{\partial u}{\partial z}\right\}-\xi\frac{Av^2}{xV_F}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+G_x+f_x-b_x-\frac{R_{\mathrm{SOR}}}{\rho V_F}\left(u-u_{\mathrm{w}}-\delta u_s\right)\\
&\frac{\partial v}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial x}+wA_z\frac{\partial u}{\partial z}\right\}+\xi\frac{A_y uv}{xV_F}=-\frac{1}{\rho}\left(R\frac{\partial p}{\partial y}\right)+G_y+f_y-b_y-\frac{R_{\mathrm{SOR}}}{\rho V_F}\left(v-v_{\mathrm{w}}-\delta v_s\right)\\
&\frac{\partial w}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial x}+wA_z\frac{\partial u}{\partial z}\right\}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+G_z+f_z-b_z-\frac{R_{\mathrm{SOR}}}{\rho V_F}\left(w-w_{\mathrm{w}}-\delta w_s\right)
\end{aligned} \tag{3}$$

The authors use the RNG model to solve the turbulence equations for all scenarios. RNG is known for its ability to simulate the strong shear zones of the flow more accurately in accordance with the characteristics of the simulation scenarios [9]. The RNG model uses the integration technique, calculating the turbulence kinetic energy k_t and the kinetic energy dissipation rate ε_t. The RNG model relies less on fixed empirical constants and instead uses the turbulence scale to determine the parameters that vary according to the cases [10]. The minimum rate of turbulence energy dissipation rate ε_T is limited by the following equation:

$$\varepsilon_{T,\min}=C_v\sqrt{\frac{3k_T^{\ 3/2}}{2T_{LEN}}} \tag{4}$$

where C_v is a parameter (default value is 0.09), k_t is the turbulence kinetic energy and T_{LEN} is the length scale. The constant value for this length scale is chosen according to the 7% rule of the size of the dominant moving object. Details of the turbulence models and the corresponding equation models are available in [8].

3.2. Domain and meshing

The domain is selected appropriately to ensure the computer's simulation capability, but it needs to be large enough to stabilize the incident wave conditions and accurately reflect the interaction between the submerged breakwater structure and the environment. The size of the submerged breakwater block is selected at a ratio of 1:1 compared to the physical model. To damp the transmitted wave after passing the breakwater, a wave absorber was installed at the end of the model. The detail of the model is presented in Fig. 6, in which

Model size: Width × height × length = (1.0 × 1.5 × 45.0) m.

Distance from wave generator to toe slope: 20 m = 5Ls (ensure wave reaching the construction is stable).

Wave absorbing: Width × height × length = (1.0 × 1.0 × 7.0) m.

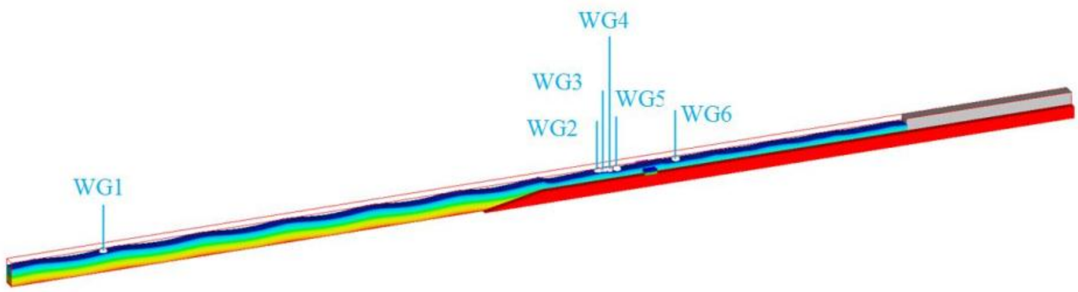


Fig. 6. Layout of domain size.

The appropriate grid size for the calculation cell is a very important task. This value is balanced based on the accuracy of the model and the simulation calculation time. Therefore, the number of calculation grid cells needs to be controlled as little as possible but still ensure sufficient resolution and acceptable error of the simulation problem. Based on the results of model calibration and verification, the authors choose a uniform grid size of 0.01 m.

3.3. Boundary conditions

a) Model boundary

Boundary conditions in the model are shown in Fig. 7. Waves and flows are calculated on a 6-face Cartesian coordinate system in which in the X direction, the wave-generating boundary is X_{min} - Wave, the boundary of the outgoing flow is X_{max} - Outflow; in the Y direction, the left wall is assigned Y_{min} - Symmetry and the right wall is assigned Y_{max} - Symmetry; in the Z direction, the lowest boundary is assigned Z_{min} - Wall, the largest boundary is assigned Z_{max} - Specified pressure.

The initial state at time $t = 0$ is set to determine the initial condition of the simulation scenario, the authors use the water level elevation parameter.

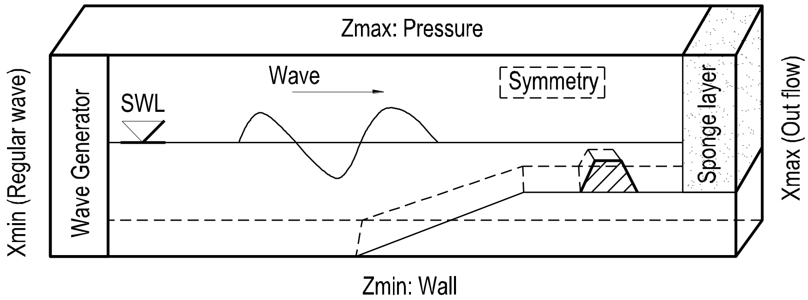


Fig. 7. Boundary conditions of the model.

b) Wave conditions

The model regular incident wave is set at the X_{min} and is propagated straight along the X direction.

c) Model

- FLOW-3D's porous media model is used to simulate the interaction of the PCSB with the incident waves;

- The PCSB's porosity is set via the porous component at a ratio of 1:1 compared to the physical model.

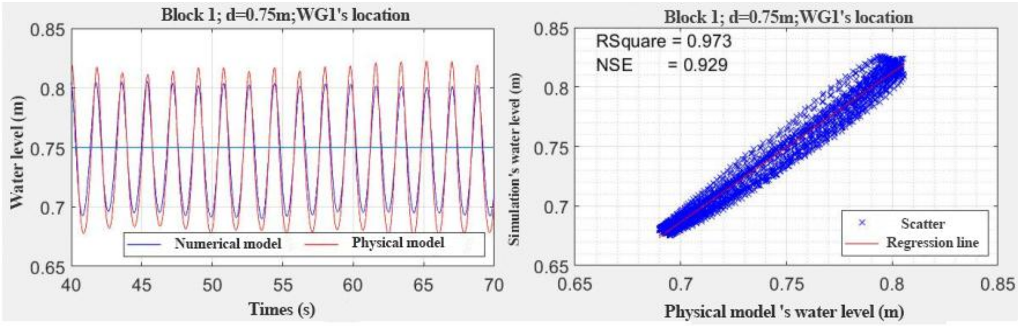
3.4. Calibration of model

The author calibrated the model on the following parameters: mesh size, turbulence model, surface roughness. Based on the results of physical model experiments, the following model parameter set was proposed:

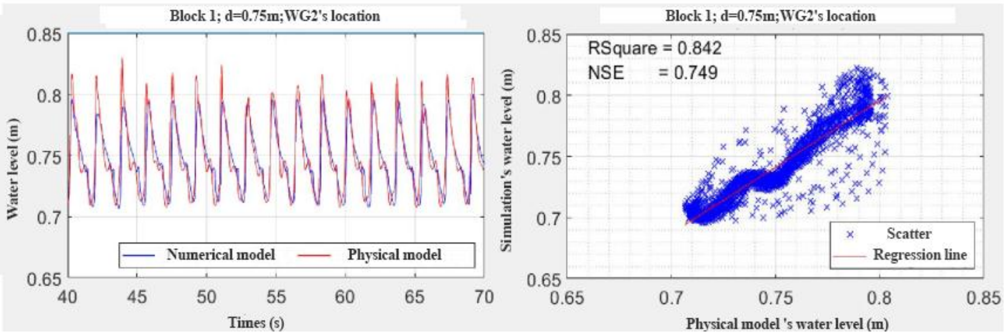
- Turbulence model RNG;
- Mesh size 0.01 m;
- Surface roughness: 0.017 for slope and 0.035 for PCSB.

To verify the accuracy and correlation between the model and experimental works, Authors use two parameters Rsquare (Coefficient of Determination) and NSE (Nash Scutcliffe model efficiency coefficient) as Fig. 8.

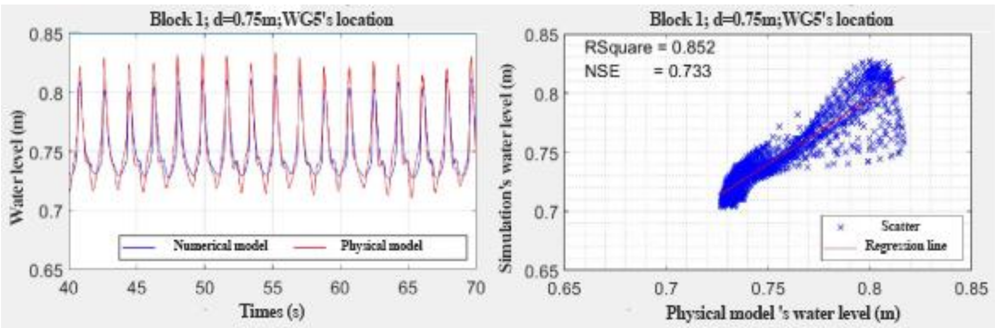
The results extracted at the survey cross-sections shown in Fig. 8 that the simulation results are consistent with the physical model. The Rsq > 0.67, the NSE > 0.615. Comparison to the qualification of error ranges of the process parameters according to V. Rijn *et al*. [11] the model completely ensures reliability to carry out further research.



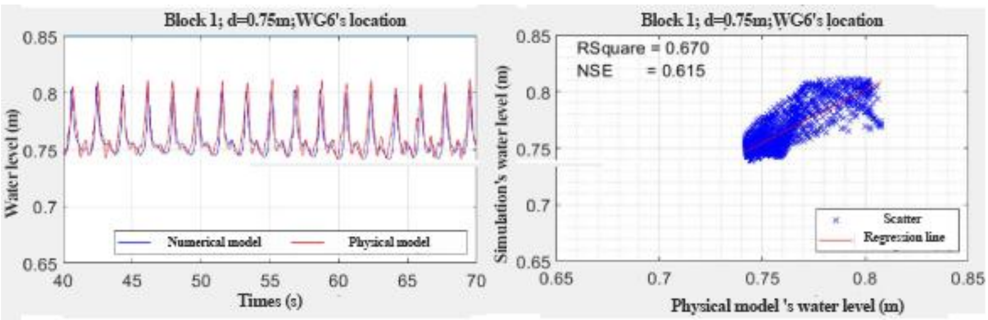
a) Section WG1 - Deep water waves



b) Section WG2 - Waves on platform



c) Section WG5 - Incident wave at the toe of PCSB



d) Section WG6 - Transmited wave behind the PCSB

Fig. 8. Model calibration results.

3.5. Scenario

In order to study the wave reduction efficiency of PCSB, the authors conducted a survey on 4 groups of scenarios: Changing the porosity ε, freeboard *S/H*, the crest width *B/L*, and the slope coefficient *m*. Details are specified as Tab. 1 below.

Tab. 1. Summary of research scenarios

No.	Script	Parameter change	Wave parameters
1	Scenario 1	Porisity (5 levels): 0.15 (rand multiple components and one component), 0.20, 0.25, 0.30, 0.35	d = 0.75 m, Hs = 0.1 m, Tp = 1.6 s
2	Scenario 2	Freeboard	
2	Scenario 3	Crest width (6 levels): 0.5 m, 0.75 m, 1.0 m, 1.25 m, 2.0 m, 2.5 m; porisity 0.15	
3	Scenario 4	Slope (3 levels): 1.5, 2.0, 3.0; porisity 0.15	

4. Results and discussions

Deep water waves reaching the PCSB are deformed due to the seabed and interaction with the PCSB.

4.1. Case 1 - Changing porosity

The results in Fig. 9 show that the porosity of the structure is inversely proportional to the wave reduction efficiency of the structure.

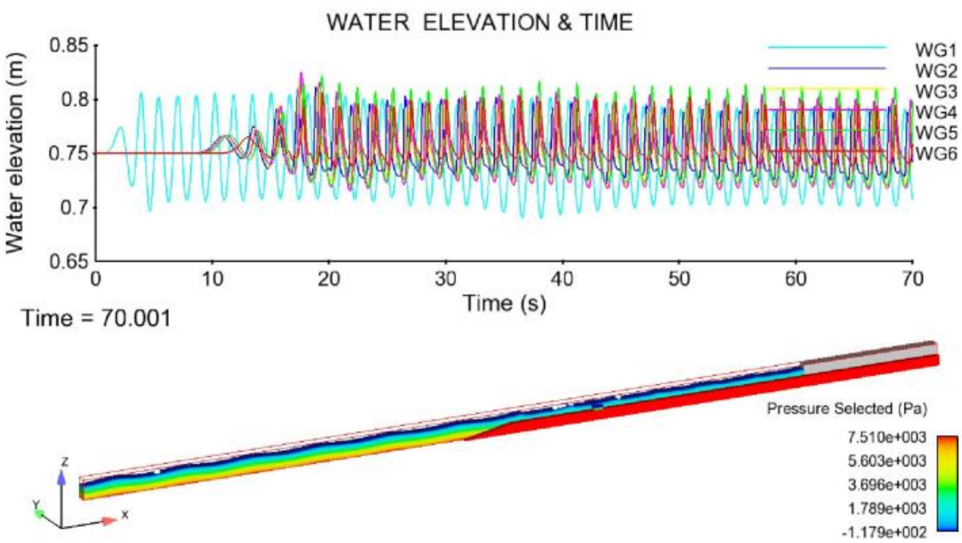


Fig. 9. Water level at measuring points.

The simulation results in Fig. 10 show that under the same wave conditions, when changing the arrangement of the structure, the wave height reduction change fairly.

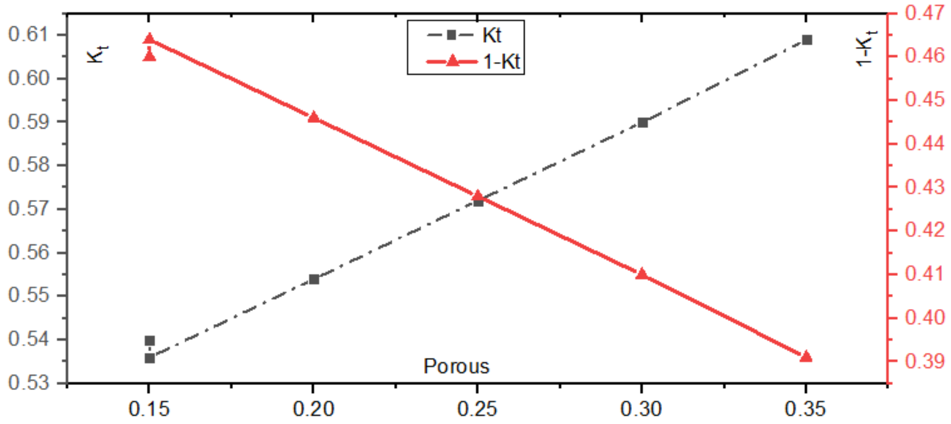


Fig. 10. Wave reduction index.

In detail, with CK1 and CK2, the average porosity is 20%, the wave reduction efficiency K_t is 0.544 and 0.54, respectively. The porosity of the porous concrete block significantly changes the wave reduction efficiency of the PCSB. The higher the porosity, the lower the wave reduction efficiency of the structure and vice versa. This result has evaluated the wave reduction efficiency of the submerged breakwater using porous concrete blocks with different porosity, thereby providing an overview in choosing the most suitable porosity.

4.2. Case 2 - Changing freeboard

The freeboard is an important parameter that determines the wave reduction efficiency of the PCSB.

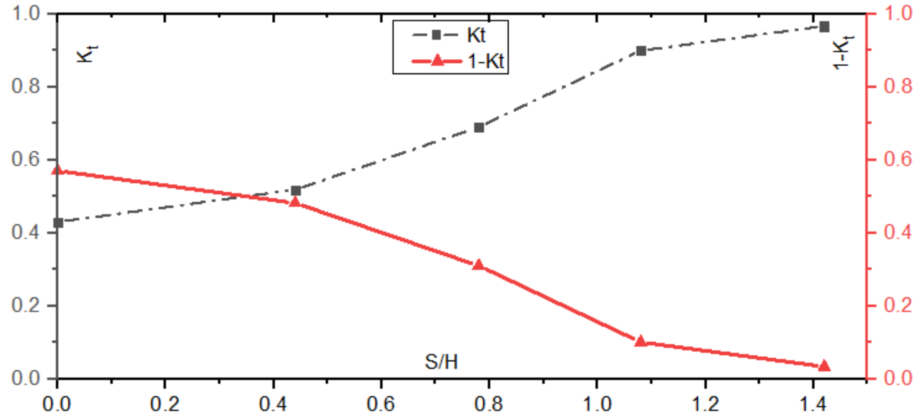


Fig. 11. Wave reduction index.

In this study, the authors survey it at different levels S = 0.0, 0.05, 0.1, 0.15, and

0.2 (m). The wave parameter H = 0.10 m, T = 1.6 s, and the structure size are fixed.

The simulation results in Fig. 11 show that, under the same conditions of geometry and wave conditions, the wave reduction efficiency of the PCSB varies greatly depending on the freeboard. The PCSB has no value when the freeboard is relatively high with incident wave height.

4.3. Case 3 - Changing the width crest

To evaluate the influence of the width crest on the wave reduction efficiency of the PCSB, wave propagation simulations passing over the breakwater were performed corresponding to the cases of width crest changes B = 0.5 m, 0.75 m, 1.0 m, 1.25 m, 2.0 m, and 2.5 m (Fig. 12). Other factors such as freeboard and wave parameters were unchanged (S = 0.05 m, Hs = 0.10 m, Tp = 1.6 s).

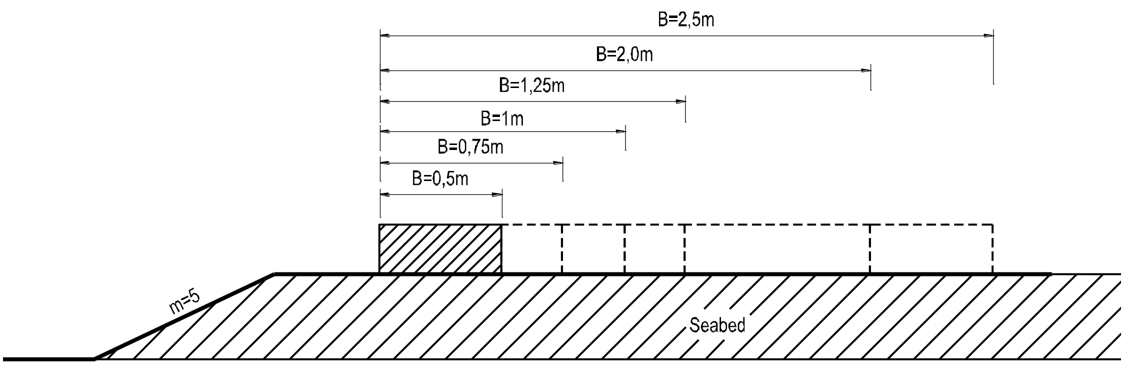


Fig. 12. Changing the width of the breakwater crest.

From Fig. 13, it can be seen that under the same hydraulic conditions, the wider width crest, the higher the wave reduction efficiency. When the breakwater crest is too wide *B/L* > 0.5, the wave reduction efficiency passing over the PCSB increases slowly and becomes less effective.

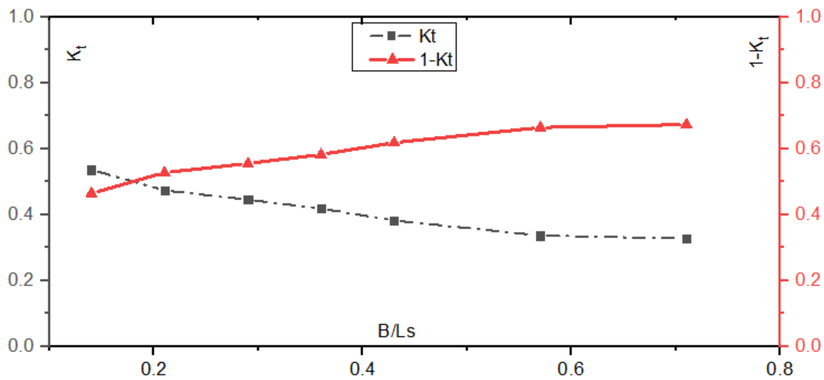


Fig. 13. Wave reduction index.

4.4. Case 4 - Changing slope

One of the factors affecting the wave reduction efficiency of PCSB is the breakwater slope. In this paper, the slope coefficient is changed to m = 1.5, 2.0, and 3.0 (Fig. 14). These are common breakwater slope coefficients in practice, depending on specific construction conditions, hydraulic conditions such as freeboard, crest width and wave parameters are stable (S = 0.05 m, Hs = 0.10 m, Tp = 1.6 s).

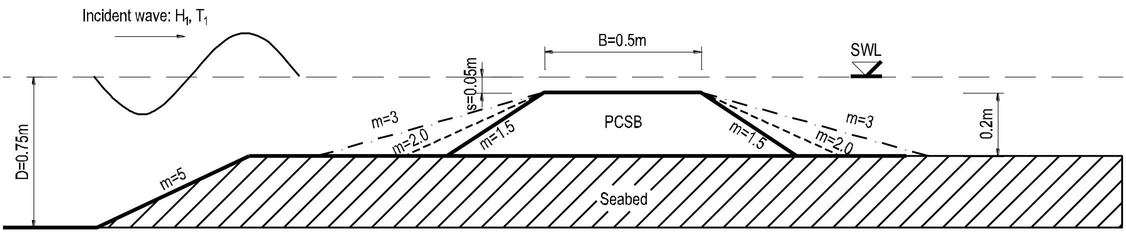


Fig. 14. Changing the breakwater slope.

The results in Fig. 15 show that the wave reduction efficiency of PCSB breakwaters with a steeper slope increases the wave reduction efficiency.

In fact, the range of variation of the breakwater slope coefficient is even narrower because the submerged breakwater is protected by a cover layer with a fairly large slope (m = 1.5 or 2.0) to provide hydraulic stability. Therefore, the breakwater slope coefficient is only a secondary parameter and a typical breakwater slope coefficient should be used in physical model experiments to evaluate the wave reduction efficiency of the submerged breakwater later.

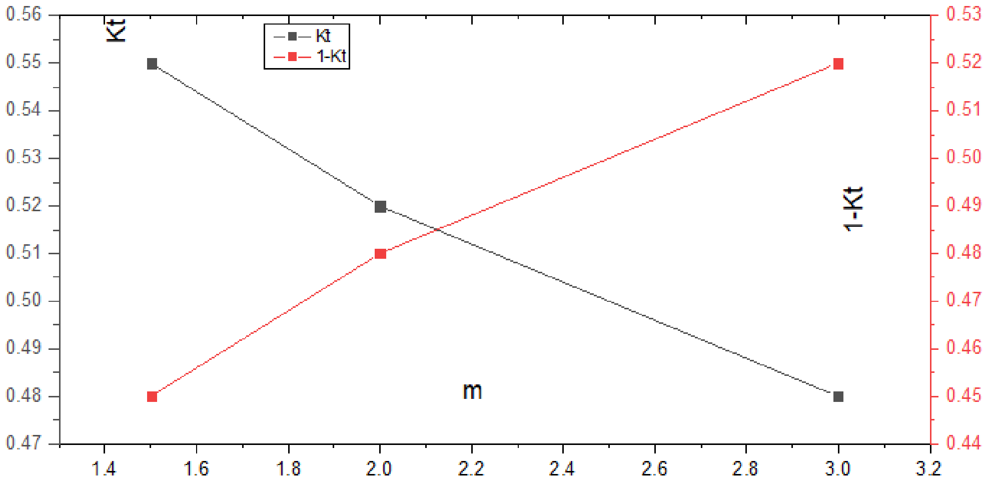


Fig. 15. Wave reduction index.

5. Conclusion

The simulation results from the FLOW-3D software have been verified with the experimental results of the physical model with very high accuracy, the wave reduction efficiency of the PCSB changes little when the porosity is randomly arranged. Changing the components with different porosity affects the wave reduction efficiency of the structure. The relative freeboard and the crest width are two important parameters that determine the wave reduction efficiency of the PCSB.

Because random wave simulation requires time and high machine configuration, the new study is only for regular waves. The authors will continue to simulate the interaction of PCSB with random waves in future studies to be closer to practical conditions.

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KHẢ NĂNG GIẢM SÓNG QUA ĐÊ NGẦM SỬ DỤNG KẾT CẤU BÊ TÔNG RỖNG BẰNG PHẦN MỀM FLOW-3D

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Tóm tắt: Bài báo trình bày kết quả nghiên cứu hiệu quả giảm sóng của đê ngầm sử dụng kết cấu bê tông rỗng (PCSB) bằng phầm mềm FLOW-3D. Các kịch bản được mô phỏng trên mô hình có kích thước: dài × rộng × cao = (45 × 1,0 × 1,5) m với 4 nhóm kịch bản khảo sát: độ rỗng khối đê ngầm, tỉ lệ độ ngập đỉnh đê với chiều cao sóng tới *S/H*, chiều rộng đỉnh đê trên chiều dài sóng *B/L* và độ dốc mái đê. Kết quả mô phỏng được hiệu chỉnh và kiểm định với dữ liệu thực nghiệm tại các mặt cắt khác nhau cho thấy sự phù hợp cao. Nghiên cứu này làm sáng tỏ cơ chế lan truyền, hấp phụ sóng qua kết cấu PCSB. Khi được bố trí phù hợp, hiệu quả giảm sóng của kết cấu PCSB được thể hiện bằng chiều cao sóng sau đê và chiều cao sóng tới, từ đó cho thấy khả năng áp dụng hiệu quả dạng kết cấu này trong thực tế. Phần mềm FLOW-3D được áp dụng trong nghiên cứu này đóng vai trò là công cụ phân tích biến dạng sóng qua PCSB sẽ góp phần quan trọng trong việc thiết kế dạng kết cấu này như một biện pháp hiệu quả bảo vệ bờ biển.

Từ khóa: *Bê tông rỗng; giảm sóng; đê ngầm; phần mềm FLOW-3D.*

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