

EXPERIMENTAL AND NUMERICAL STUDY ON WAVE REDUCTION BY TWO PERMEABLE SUBMERGED BREAKWATERS

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ABSTRACT

This study presents an experimental and numerical study of incident wave reduction and transmission coefficients for impermeable and permeable double submerged breakwaters. The experiments were carried out by constructing an immersed breakwater using gravel in a physical wave tank. Numerical analyses were performed using a two-dimensional fully nonlinear numerical wave tank consisting of a fluid domain and a porous domain. The transmission coefficient of the incident wave was small for the permeable submerged breakwater, and the smallest for the Bragg reflection condition with the gap of the breakwater.

INTRODUCTION

Breakwaters are the simplest and most effective way to prevent wave inundation of coastal areas and harbors. However, fixed breakwaters that protrude above the water surface can disrupt coastal current flow and alter the coastal environment. Floating breakwaters have been designed to overcome this problem, but there are difficulties in designing mooring lines due to large tides, and aesthetic problems such as protruding into the water surface like fixed breakwaters. Seabed fixed breakwaters, which can overcome these problems, are an effective alternative that does not cause aesthetic problems or interfere with the passage of ships, as long as the breakwater performance can be secured. In this study, to maximize the performance of the seabed fixed breakwater, two submerged structures were installed at a certain distance apart, and the surface of the breakwater was made permeable to absorb wave energy to maximize the breakwater performance. In particular, by installing each immersed structure at a distance of $1/2$ of the incident wavelength, the incident wave height was reduced through the Bragg reflection effect. There are not many studies on permeable seabed breakwaters compared to impermeable breakwaters. The reduction of incident waves by the immersed structure was carried out through experimental and numerical analyses. The transmission coefficient was calculated by comparing the incident wave height and transmission wave height. The performance of permeable breakwaters was investigated by comparing the wave transmission coefficients of permeable and impermeable breakwaters. Experiments were conducted using a two-dimensional wave tank. The permeable breakwater was constructed with pipes and gravel was placed in the structure to obtain the appropriate permeability coefficient. To numerically simulate the wave propagation over the permeable submerged structure, a two-dimensional fully nonlinear numerical wave tank (FN-NWT) was used. The FN-NWT is based on the boundary

element method (BEM) and consists of dual domains (fluid and porous domains). A mixed Eulerian-Lagrangian (MEL) method was applied to update the nonlinear free surface boundaries, and a three-step method was used to compute the interaction between the fluid and porous domains (Min et al., 2023).

EXPERIMENTAL SETUP

The experimental study was conducted using a two-dimensional mini wave tank in INHA University, which was 6 m long (L), 0.3 m width (W), and 0.5 m depth (H). A piston-type wave maker was used to generate incident waves, and a wave absorber in the form of a punching plate was installed to minimize reflected waves from the end-wall of the tank. More details about the wave tank were provided in Jung and Koo (2021). Wave reduction experiments for the submerged breakwater were performed for two types of structures: impermeable and permeable. The impermeable structures were made of zinc pipes, while the permeable structures were made of boxes and filled with gravel. The average diameter (d_{50}) of the gravel is between 0.03 and 0.04 meters.

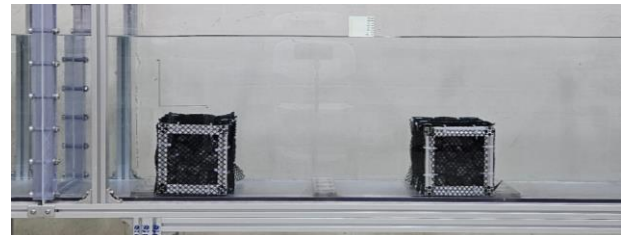


Figure 1 - Experimental Set-up for Two Permeable Submerged Breakwaters

MATHEMATICAL FORMULATIONS

Numerical analysis was performed to validate the experimental data. The interaction between the incident wave and the submerged breakwaters was analyzed in the time domain using FN-NWT. First, the fluid domain is assumed to be incompressible, irrotational and inviscid, and the Laplace equation is applied as the governing equation (Eq. 1) for the velocity potential (ϕ).

$$\nabla^2 \phi = 0 \quad (1)$$

The boundary conditions for the fluid domain are defined as follows. The incident wave boundary conditions were applied up to the Stokes' 2nd-order wave term.

$$\frac{\partial \phi}{\partial n} = \frac{gH_I k \cosh k(z+h)}{2\omega \cosh kh} \cos(kx - \omega t) n_x + \frac{3H_I^2}{4} \omega k \frac{\cosh 2k(z+h)}{\sinh^4 kh} \cos 2(kx - \omega t) n_x \quad (2)$$

where g is the gravitational acceleration; H_I is incident wave height; k is wave number; ω is wave frequency; h is water depth; n_x is the x-directional normal vector. To deal with nonlinear free surface boundary conditions and nodes, the MEL method was applied, and the boundary conditions were rearranged by the total derivative and material node approach.

$$\frac{\delta \phi}{\delta t} = -g\eta + \frac{1}{2} |\nabla \phi|^2 \quad (3)$$

$$\vec{x} = \nabla \phi \quad (4)$$

where η is free surface elevation. To minimize wave reflection from the end wall of the computational domain, an artificial damping term was added to the free surface boundary condition. A non-Darcy (Forchheimer) flow condition was applied for the permeable boundary condition.

$$\nabla p_s = -\left(\frac{\mu}{K} + \beta_F \rho |\vec{u}|\right) \vec{u} \quad (5)$$

where K is the permeability coefficient; μ is the dynamic viscosity of the fluid; ρ is the fluid density; β_F is non-Darcy factor; \vec{u} is the discharge velocity. Rigid boundary condition for end-wall and bottom of the tank is as follows.

$$\frac{\partial \phi}{\partial n} = 0 \quad (6)$$

The permeable submerged breakwater is set to be a porous domain, and the flow inside the porous domain is assumed to satisfy Darcy's law and incompressible flow ($\nabla \vec{u} = 0$).

$$\nabla^2 p_s = 0 \quad (7)$$

The hydrodynamic pressure exerted on the submerged breakwater is

$$p_s = -\rho \left(\frac{\partial \phi}{\partial t} + \frac{1}{2} |\nabla \phi|^2 \right) \quad (8)$$

The bottom boundary condition of the submerged structure applied rigid boundary condition.

$$\frac{\partial p_s}{\partial n} = 0 \quad (9)$$

To compute the interaction between the fluid and porous domains, a three-step calculation technique was applied. This technique involves solving the boundary value problem for the fluid and porous domains three times at each time step. More details can be found in Min et al. (2023).

RESULTS

Figure 2 shows the overall computational domain for the numerical analysis. The water depth (h) is set to 0.35 m, the wave period (T) is 0.8~1.2 s, the incident wave height (H_I) is 0.013~0.016 m, the width (W_b) and height (H_b) of the structure are set to $W_b = H_b = 0.15$ m, and the spacing (L_b) of the submerged breakwater is set to 0.8 m. Figure 3 presents the transmission coefficients of incident waves

for impermeable and permeable structures from experimental results. The transmission coefficient (K_T) is defined as $K_T = H_T/H_I$.

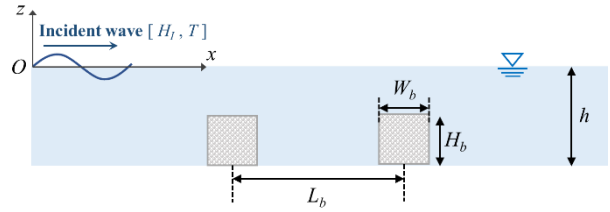


Figure 2 - Computational domain for wave propagation over a double submerged breakwater

The transmission coefficient was smallest around $kh=1.4$, which may be related to the Bragg reflection characteristics, where the reflected wave is maximized when the distance between the two structures is half the wavelength. The difference in transmission coefficient between the impermeable and permeable structures was also largest around $kh=1.4$ ($kh=1.43$, $T=1.05$ s). As the height of the structure increases, the effect of the submerged structure on the transmitted wave increases.

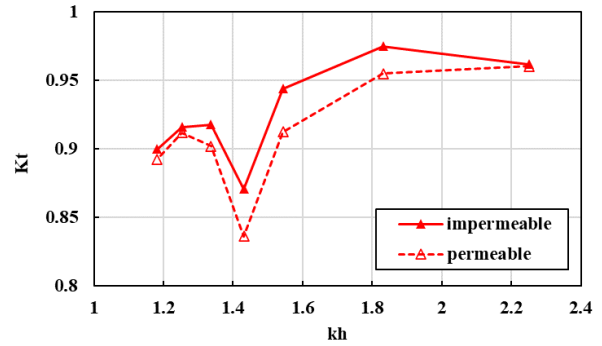


Figure 3 - Comparison of transmission coefficients for various wave conditions [$W_b = H_b = 0.15$ m, $L_b = 0.8$ m]

CONCLUSIONS

Experimental and numerical studies of the transmission coefficients of incident waves for impermeable and permeable submerged breakwaters were conducted. The transmission coefficient of the incident wave was small in the permeable submerged breakwater, with the smallest at $kh=1.4$ due to the Bragg reflection along the gap of the breakwater.

REFERENCES

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