Computational Analysis of Stability of Wave Propagation Against Submerged Permeable Breakwater Using Hybrid Finite Element Method

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Article

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Abstract: A wave is an energy that can propagate with a medium, the propagation of a wave moves with respect to time by carrying energy that moves with velocity per unit of time. Sea waves are one of the propagating wave problems that are broken down to produce wave propagation with a relatively inhomogeneous minimum amplitude and speed of sea waves which have their own difficulties in solving them numerically. This study aims to analyze the stability of wave propagation of submerged breakwaters using the Boundary Element Method. This research will approximate the boundary discretization of the breakwater domain and then combine it with the Finite Element Method in determining the moving elements of the velocity of fluid flow through a porous submerged breakwater. This study varies the magnitude of the incoming propagation velocity and the influence of the breakwater distance. The results of this study indicate that the resulting minimal wave assuming v = 1 m/s and the breakwater distance of s = 20 m gives a wave reflection with a minimum wave speed and amplitude of 0.12515 m.

Keywords: Breakwater; Simulation; Fluids Dynamics; H-FEM; PDE

1. Introduction

A wave is a propagating vibration that propagates in a medium or a set of objects that interact with each other. Real examples of waves can be seen in surface wave problems such as ocean waves on the beach. Waves on the surface of the water are a process of interaction between moving air masses and meeting the surface layer of water. This interaction produces a pattern of peaks and valleys which is influenced by the presence of energy and momentum. Basically, surface water waves are not only caused by air masses, but these waves can also be caused by other activities that exist at the bottom of the water depth. [1,2] explains, the propagation speed of surface water waves depends on the water surface tension, hydrostatic pressure, bottom depth, mass density, and gravity. The waves that occur on the surface of the water are caused by several things, such as wind blowing or vibrations at the bottom of the water, for example tsunami waves. [3–5].

[6,7] in his research conducted a study on how to reduce the strength of waves at sea level using a breakwater in the form of a porous block. The first thing to do in this research is to form a wave model of the surface of the water through a breakwater in the form of a porous block. The model is formed using the governing equations for surface waves passing through porous beams, namely the continuity equation, momentum equation, potential wave velocity, fluid in porous media, Laplace and Bernoulli equations in fluid and porous media, as well as kinematic and dynamic boundary conditions on the surface. fluid. The resulting model is almost similar to the shallow water equation. In the next procedure, [8–10] explains how to find a numerical solution from the model that has been formed. The solution of the numerical solution in the model is carried out by finite difference method implicit scheme corrector predictor. The results of the research conducted explain that the wave amplitude after going through the breakwater has decreased. The attenuation or attenuation of wave strength

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depends on the number of breakwaters and the height of the breakwaters. In this study the authors will simulate wave breaking using a submerged porous breakwater to find a numerical solution using the Boundary Element Method. Boundary Element Method is one of the approaches that can be used to solve various types of differential equations. Solving the equation is done by discretizing the equation with initial conditions and boundary conditions, then determining the stability of the equation discretization. [11] explains that the boundary element method is a method based on the Taylor series expansion [12]. One approach with the finite difference method is to use an implicit schema. Implicit schemas have the advantage that they are unconditionally stable. The time step Δt can be taken arbitrarily (large) without causing instability. [13]

Research on breakwaters aims to determine the phenomena that occur with the energy generated from the movement of seawater moving towards coastal areas which are shallow areas [14–17]. The development of research on breakwaters has been carried out by several mathematicians-physicists who focus on breakwater models [18,19]. In research that has been done, breakwaters with different dimensions will produce different results according to the specified model parameters. In terms of optimizing the breakwater model, it is influenced by several important parameters such as the wave velocity, wave height, depth, pressure, and even Newtonian force which results in momentum in the breakwater [20,21]. In his research, he explained how the analysis of the interaction between models of breakwaters used in three-dimensional problems with porous breakwater models by developing equations from the Navier-Stokes equations resulted in a 3D wave propagation model for surface emerging breakwaters [22,23]. Many simulations of breakwaters have been carried out to find out how much wave reduction is produced from both the speed and wave height values [24–26]. Simulation involving different parameters will give complex results in its completion because it is necessary to do a multi-purpose programming model [27,28]. The results of research with a focus on wave propagation stability analysis [29,30] need to consider the magnitude of the reduction of the incident wave so that the amplitude value delivered to the shallow area is at a steady state point. Research on the stability of wave propagation has been carried out [31–34] to determine the factors that affect stability wave propagation in terms of wave propagation reliability, breakwater reliability and also the probability density function (PDF) value. The resulting impact of large waves is damage to shallow areas and even coastal areas as critical areas [35–37]. The optimal wave splitting process aims to reduce the magnitude of wave resonance at the harbor by applying the Helmholtz equation which has complex values as the model state equation with minimizing wave amplitude as the optimization variable [11,38]. The author proposes that a sinking breakwater will provide momentum resistance to subsurface currents so that the amount of momentum that occurs will be reduced from the bottom of the shallow area before the wave propagates to the coastal area [39,40]. The results to be achieved from this study are simulations of wave height (λ) from variations in the depth of the breakwater position from the sea surface. This study will also simulate the effect of speed variations on the amplitude of the waves that occur. The formation of a sinking breakwater model will be carried out by testing the reliability of moving against time to reach the stability area against the variations of constraints that are carried out.

2. Materials and Methods

2.1. Breakwater Simulation

Submersible breakwaters are facilities built to break waves under the surface of the water with the aim of dampening and absorbing internal energy from wave propagation underwater. Based on the principle of hydrostatic pressure that the greatest water pressure is at the bottom of the sea water which is expressed by the pressure P of water directly proportional to the depth of sea water h [41–43]. Hydrostatic pressure is expressed as:

$$-\delta P = g\rho\delta z \tag{1}$$

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where, lim $\delta z \rightarrow 0$ and the eq (1) can be expressed as:

$$\frac{\partial P}{\partial z} = -g\rho \tag{2}$$

write that $P, g, \rho, \partial z$ respectively represent hydrostatic pressure, gravitational acceleration, fluid density, and changes in water depth [44]. Eq (1) is written with a negative sign with the assumption that the pressure P will decrease with increasing height which is applied to the problem of hydrostatic pressure in the case of an object moving towards the atmosphere. For the sinking breakwater problem, Eq (1) will be an increase in $\partial \ddagger$ which will result in an increase in pressure P so that the pressure will be greater in the bottom area [45]. The submerged breakwater will absorb some of the energy from the bottom area with the aim of reducing the amount of energy that is in the surface area. An illustration of the wave breaking process with a breakwater is shown in Figure 1.

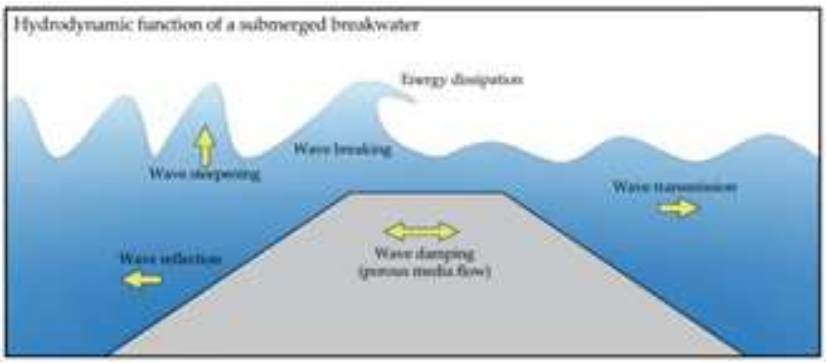

Figure 1. Submerged Permeable Breakwater Simulation.

The sinking breakwater will absorb some of the inner energy at the bottom of the wave by releasing the wave propagation that hits the breakwater so that a process of changing momentum occurs in the wave propagation [46–48]. The process of breaking waves with a sinking type is often used to control large-scale wave propagation for coastal areas or port areas which maintain the magnitude of wave propagation in coastal areas [49].

2.2. Navier-Stokes Equation on Moving Fluids

The Navier-Stokes equation is a mathematical discipline that formulates fluid problems both for fluids and for the characteristics of fluids [50–54]. The Navier-Stokes equation modeling describes how the value of the velocity vector propagates through the u, v components at the x, y coordinates that move with time. In vector analysis problems it is defined that all fluid quantities are functions of space over time, fluid quantities can be vector values of velocity (v) and acceleration (a) [55,56]. Let a is a vector component of velocity and time vector that can be written as:

$$\vec{a} = \left(\frac{du}{dt}, \frac{dv}{dt}\right) \tag{3}$$

denote that $\vec{a} = \frac{d\vec{v}(x,y,t)}{dt}$, consists of components in Eq (3), then by following the chain rule then the value of $\vec{a}$ for each component is:

$$\vec{a}_x = \frac{du}{dt} = \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x}\frac{dx}{dt} + \frac{\partial u}{\partial y}\frac{dy}{dt} \tag{4}$$

$$\vec{a}_y = \frac{dv}{dt} = \frac{\partial v}{\partial t} + \frac{\partial v}{\partial x}\frac{dx}{dt} + \frac{\partial v}{\partial y}\frac{dy}{dt} \tag{5}$$

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For each value of $\frac{dx}{dt}$, $\frac{dy}{dt}$ is a function of space against time which can be written respectively as u, v which results in the acceleration value in Eq (4)(5) for each components are:

$$\vec{a}_x = \frac{du}{dt} = \frac{\partial u}{\partial t} + \vec{v}.\nabla u \tag{6}$$

$$\vec{a}_y = \frac{dv}{dt} = \frac{\partial v}{\partial t} + \vec{v}.\nabla v \tag{7}$$

simply, the vector of a can be written as:

$$\vec{a} = \left(\frac{\partial}{\partial t} + \vec{v}.\nabla\right)\vec{v} \tag{8}$$

2.3. Hybrid Finite Element Method

The application of the Hybrid Finite Element Method is used by determining the initial value of a function that moves with time [57,58]. The equation using Hybrid Finite' elements will provide an efficient solution by separating the wave equation from the momentum equation then linearizing [59].

$$\int_0^{t_F^+}\int_0^r \left(\frac{\partial^2\eta}{\partial t^2} - c^2\frac{\partial^2\eta}{\partial x^2}\right)\eta^* \mathrm{dxdt} = \int_0^{t_F^+}\int_0^c B\eta^* \mathrm{dxdt} \tag{9}$$

where r is the region length and $t_F^+ = t_F + \epsilon$, where ϵ is a small arbitrary parameter. In the above expression Z^* is the fundamental solution of the one-dimensional wave operator, given by:

$$\eta^* = -\frac{1}{2C}H\left[c(t_F - t) - r\right] \tag{10}$$

in which H is the Heaviside function and $r = \|x - s\|, s$ and x indicating the source and field point positions respectively. Integrating the second-order derivatives in (5) twice by parts, the following equation is obtained:

$$\int_0^{t_F^+}\int_0^r \left(\frac{\partial^2\eta^*}{\partial t^2} - c^2\frac{\partial^2\eta^*}{\partial x^2}\right)\eta \mathrm{dxdt} + \int_0^r \left[\eta^*\frac{\partial\eta}{\partial t} - \eta\frac{\partial\eta^*}{\partial t}\right]_0^{t_F^+} dx \tag{11}$$

$$-c^2\int_0^{t_F^+}\left[\eta^*\frac{\partial\eta}{\partial x} - \eta\frac{\partial\eta^*}{\partial x}\right]_0^r \mathrm{dt} = \int_0^{t_F^+}\int_0^r B\eta^* \mathrm{dxdt}$$

Wave transmission (H_t) is the height of the wave that is transmitted through the obstacle and is measured by the transmission coefficient (K_t) calculated by the following equation [6]:

$$K_t = \frac{H_t}{H_i} = \sqrt{\frac{E_t}{E_i}} \tag{12}$$

where K_t is the wave transmission, K_i is the reflection wave, H_t is the value of $H_t = K_t \times H_i$, where H_i is the height of inlet wave, E_t is the transmission Energy, and E_i is the inlet energy. The value of transmission wave $E_t = \frac{1}{8}\rho.g.H_t$ involve ρ is the density of fluids and g is the gravity acceleration.

Theorem 1 Given J, and h as the proposition function f,g for $[u_0, v_0] \in H_0^1(\Omega) \times L^2(\Omega)$, there exists a unique function $J \times \Omega \to \mathbb{R}$ that satisfies the equation

$$\frac{\partial^2 u}{\partial t^2} - \Delta u + f(u) + g(\frac{\partial u}{\partial t}) = h(t,x) \text{ in } C(J, H^{-1}(\Omega)).$$

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that fulfills the condition v = value $\varepsilon \in C^1(J)$ and all t ∈ J

$$\frac{d}{dt}\left(\varepsilon\left(t\right)\right) = \int_{\Omega}\left[h\left(t,x\right) - g\left(\frac{\partial u}{\partial t}\left(t,x\right)\right)\right]\frac{\partial u}{\partial t}\left(t,x\right)dx. \tag{13}$$

Proof. The result of the existence of unique values is in the general model of the classical method combined with the prior estimation mapping on the maximum interval. Precisely, if formed $J_\delta \cap [-\delta,\delta]$ for each $\delta > 0$ for all $P > \sup\{|u_0|,|v_0|\}$, The set X endowed with the topology of $C\left(J_\delta,V\right) \cap C^1\left(J_\delta,H\right)$ is a complete metric space, for the value $v \in X$, given $C(v)$ is the unique solution of $z \in C(J_\delta,V) \cap C^1(J_\delta,H) \cap C^2(J_\delta,V')$ from the problem

$$\frac{\partial^2 z}{\partial t^2} - \Delta z = h\left(t,x\right) - f\left(v\right) - g\left(\frac{\partial v}{\partial t}\right) \tag{14}$$

$$z(0) = u_0, \frac{\partial z}{\partial t}(0) = v_0 \tag{15}$$

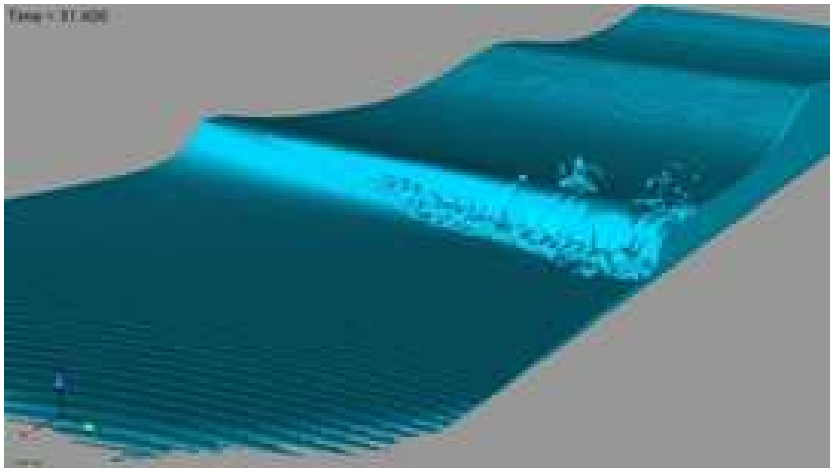

Figure 2. Wave Simulation

2.4. Wave Attenuation Equation Model

Based on the derivation of the unhindered homogeneous wave equation model in Eq (15), a wave equation model will be formed with the damping of the breakwater which is influenced by external forces that inhibit the propagation of water waves, namely the breakwater [60,61]. The wave damping process is assumed to be a modified form of the equation model by giving a negative value to the wave acceleration $(-u_{tt})$. The magnitude of the negative acceleration illustrates that the external force has a direction opposite to the direction of wave propagation, which will result in a decrease in wave height (λ) and a decrease in speed (u_t) [62–65]. Then based on the general homogeneous wave equation can be rewritten as:

$$-u_{tt} - cu_{xx} = P_x\left(t\right) \rightarrow u_{tt} + cu_{xx} = -P_x\left(t\right) \tag{16}$$

Equation (16) is solved by using the separating variable method on the interval $x(0,L)$, with the initial conditions $u\left(x,0\right) = \phi\left(x\right), u_t\left(x,0\right) = \psi\left(x\right)$ and $u\left(0,t\right) = u\left(L,t\right) = 0$. Then the solution of the homogeneous wave equation separator method is: $u_{tt} = -c^2 u_{xx}$, with $0 < x < L$, $u\left(0,t\right) = u\left(L,t\right) = 0$, $\forall t \geq 0$, $u\left(x,0\right) = \phi\left(x\right)$, with $u_t\left(x,0\right) = \psi\left(x\right)$. Furthermore, for the equation $u\left(x,t\right)$ it can be written that $u_{tt} = X\left(x\right)T''\left(t\right)$ and $u_{xx} = X''\left(x\right)T\left(t\right)$, Then the u_{tt} equation, when substituted into the separable equation above, can be written as:

$$u_{tt} = -c^2 u_{xx} \leftrightarrow X\left(x\right)T''\left(t\right) = -c^2 X''T\left(t\right), \tag{17}$$

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so,

$$\frac{T''(t)}{c^2 T(t)} = -\frac{X''(x)}{X(x)}$$

The solution to solving Eq (17) is for the problem $k = \mu^2 = \left(\frac{n\pi}{L}\right)^2$, it can be written that $\lambda_n = \frac{cn\pi}{l}$. So if the$\lambda_n$ value is substituted into Eq (17) it will produce:

$$u(x,t) = \sum_{n=1}^{\infty} u_n(x,t) = \sum_{n=1}^{\infty} \left\{ (A_n + B_n)\cos(t) + (A_n - B_n)\frac{cn\pi}{L}\sin(t) \right\} \sin\frac{n\pi}{L}x \tag{18}$$

It can be concluded that Eq (18) is a homogeneous equation in the interval $0 < x < L$. that can be written as:

$$u(x,0) = \sum_{n=1}^{\infty} (A_n + B_n)\sin\frac{n\pi}{L}x = \phi(x) \tag{19}$$

3. Results

In building a simulation of wave propagation towards a breakwater, it is necessary to initialize the wave model by determining the geometry of the wave model. At this stage a 2D wave model will be formed using COMSOL Multiphysics 5.6 as shown in Figure 3.

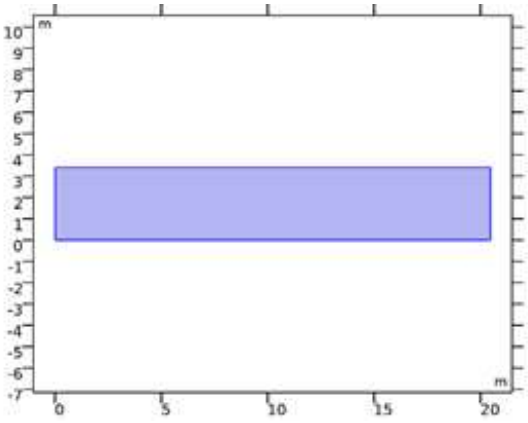

Figure 3. Breakwater Geometry Model

In the wave model, the sides that will be the inlet and outlet will be defined with the boundary conditions of each domain.

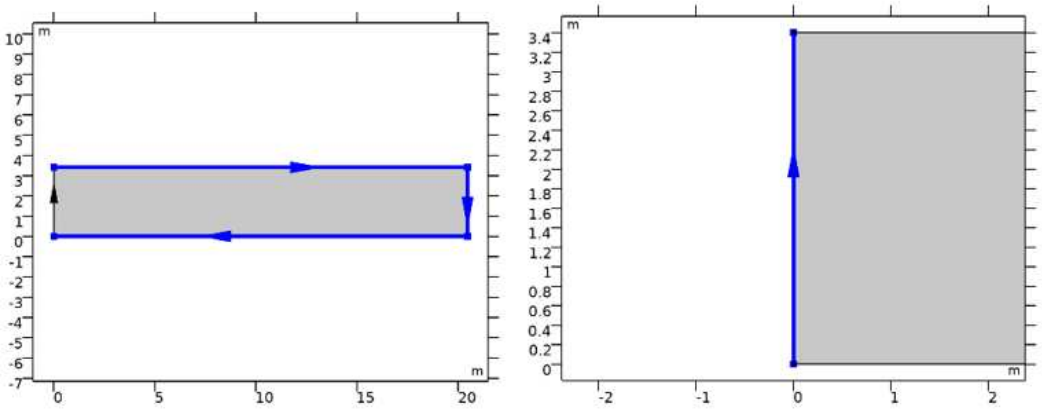

Figure 4. Inlet and Outlet Model

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The breakwater model walls in Fig (a) and (b) are formed with geometric constraints,

$$\mathbf{u}.\mathbf{n} = 0$$
$$-\mathbf{\Gamma}_h.\mathbf{n} = 0$$
$$-\mathbf{\Gamma}_h.\mathbf{n} = g\frac{h^2}{2}$$

Where the $\mathbf{u}$ and $\mathbf{n}$ vectors denote the velocity values at the coordinates $u\,(x, y, t)$ and the momentum of the flux geometry model, respectively. The $\mathbf{\Gamma}_h$ value is the magnitude of the flux conservation of the momentum at each coordinate with the calculation for each coordinate being $\mathbf{u}_x.\mathbf{q}_x + \frac{g.h^2}{2}$. In the process of meshing the model with finite elements, it was found that the size of the elements formed was 185,845 with 1,772 edges, this resulted in the need for computation in the wave model iteration so as to produce a large change in the value of the wave propagation with respect to time. In the simulation carried out, the research will test how the effect of speed on the distribution of wave velocity values after wave attenuation with each speed of $1\frac{m}{s}$, $1.5\frac{m}{s}$, and $2\frac{m}{s}$. Furthermore, the simulation will be continued with the modification of the breakwater model to the position length of the breakwater with a distance of 10 m, 15 m and 20 m respectively.

Figure 5. shows the wave breaking process with a sinking breakwater model that has permeable properties and is a propagation in shallow water, the magnitude of the velocity fraction each time is shown in Figure 6. shows the propagation of waves that propagate after a break occurs using a porous submerged breakwater. The amplitude is generated against time and oscillates up to the outlet of the propagation area. The convergence of the wave amplitudes shows that the waves resulting from the wave splitting process show significant results with as many as 4,836 iterations during $t = [0, 10]$

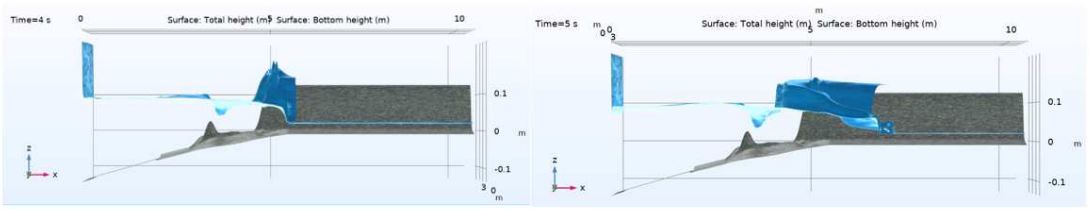

Figure 5. Breakwater Simulation

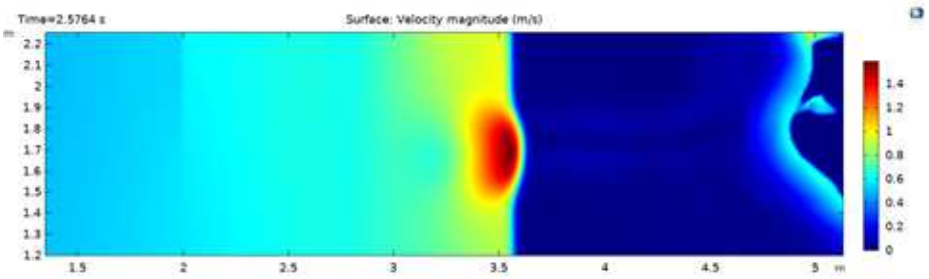

Figure 6. Simulation of the velocity of the breakwater breaking process at t = 2.5 s

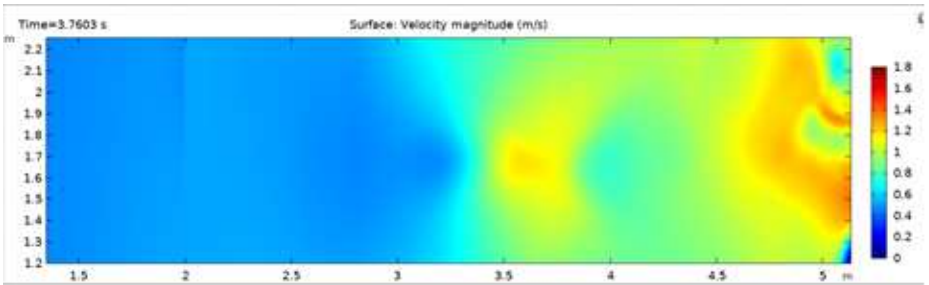

Figure 7. Simulation of the speed of the breakwater breaking process at t = 3.7 s

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Figure 8 shows the solution of the speed of wave propagation at $t = [0, 10]$ with the color representation showing the critical area experiencing the greatest velocity. Furthermore, the representation of the stability of wave propagation will be shown in Figure 9.

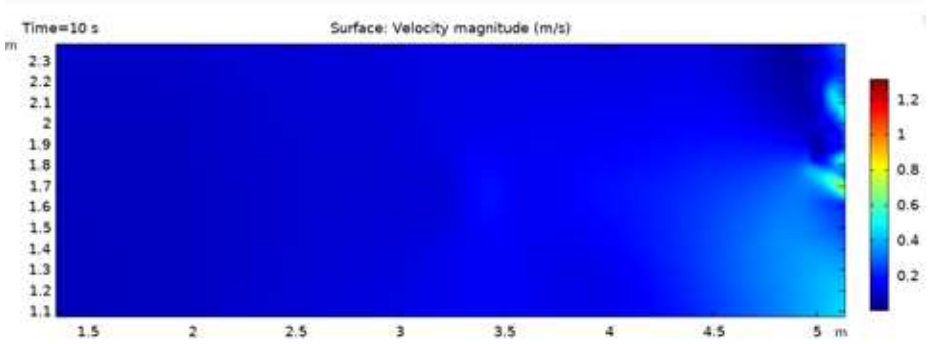

Figure 8. Simulation of the velocity of the breakwater breaking process at t = 10 s

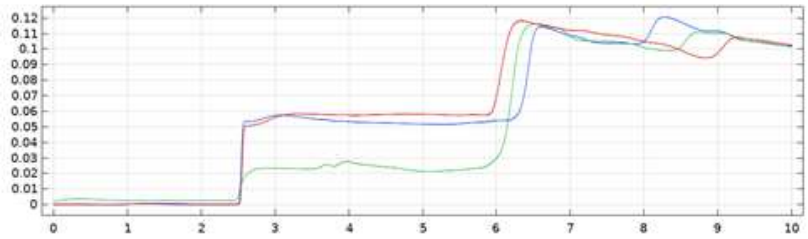

Figure 9. Water wave amplitude breaking

Figure 9 shows the propagation of waves that propagate after a break occurs using a porous submerged breakwater. The amplitude is generated against time and oscillates up to the outlet of the propagation area. The convergence of the wave amplitudes shows that the waves resulting from the wave splitting process show significant results with as many as 4,836 iterations during $t = [0, 10]$. The resolution of the wave amplitude to the elements is shown in Figure 10.

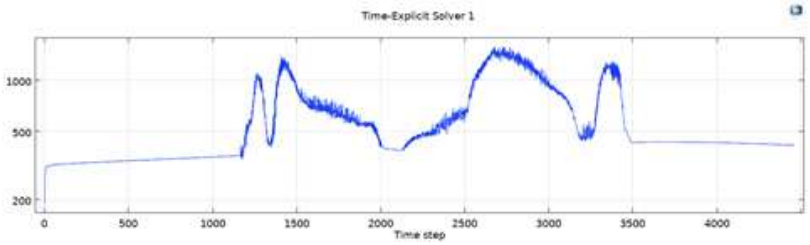

Figure 10. The results of the wave amplitude simulation in the wave breaking process

The completion iteration is carried out for 4,386 for $t = [0, 10]$. Figure 10 shows that the muted water waves show a very critical amplitude before and after the wave breaking process is carried out, the convergence of the water waves shows that the amplitude on the outlet side becomes lower in the simulation so this shows that the wave breaking process will provide amplitude attenuation and wave propagation speed the minimum. For parameter variations, a simulation is carried out on differences in wave propagation velocity of 1 m/s, 1.5 m/s, 2 m/s to see differences in the distribution of wave speed and amplitude, then the breakwater distance parameter with a constant arrival speed of 1 m/s shown in Figure 11.

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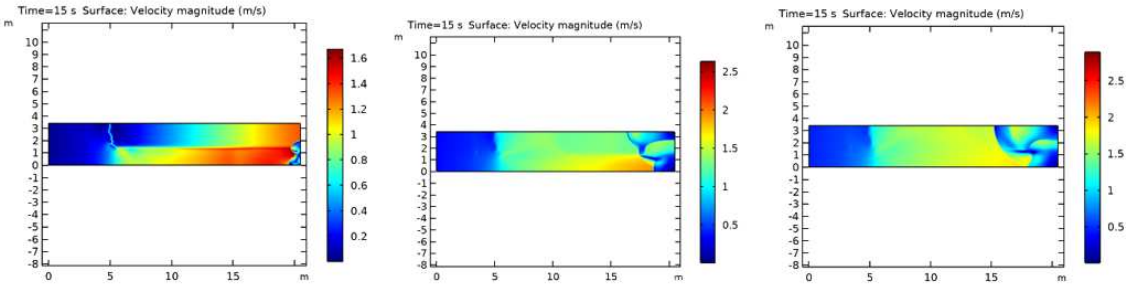

Figure 11. Resistance of Breakwaters to Changes in Speed

The breakwater will dampen the waves and break the wave propagation at each coordinate. Changes in the conservation of momentum will result in a change in the velocity value for each component at the coordinates $\mathbf{u}\,(x, y, t)$. The magnitude of the change in velocity that occurs will have an impact on the final velocity of the wave amplitude. The offshore simulation of the breakwater was carried out by modifying the geometry model of the breakwater with constant incoming wave velocity v for distance variations of 10 m, 15 m, and 20 m. The difference in the position of the breakwaters gives a different wave distribution. The model of the breakwater with changing distances is shown in Figure 12.

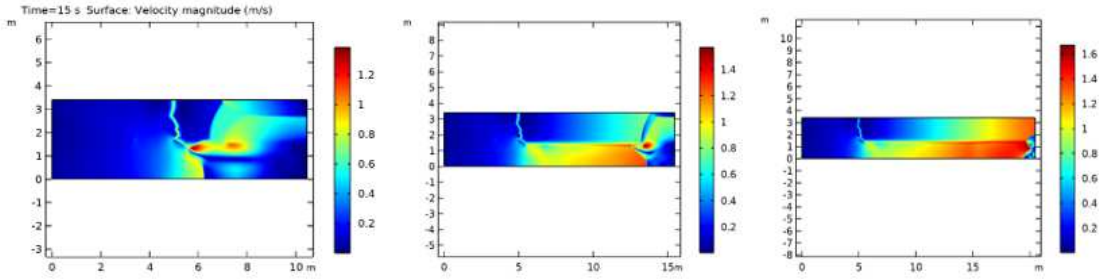

Figure 12. Changes in velocity after wave damping with variations in breakwater distance, namely (a) = 10 m, (b) = 15 m, and (c) = 20 m with conditions v=1 m/s

3.1. Stability Simulation

The stability of wave propagation is indicated by the amplitude distribution of sea water waves, given three critical points from the breakwater respectively 1.196 m, 1.696 m, and 2.196 m for variations in the distance of the breakwater, namely 9.52 m, 14.52 m, and 19.52 m. Simulation of wave amplitude distribution for variations in the position of the breakwater is shown in Figure 13.

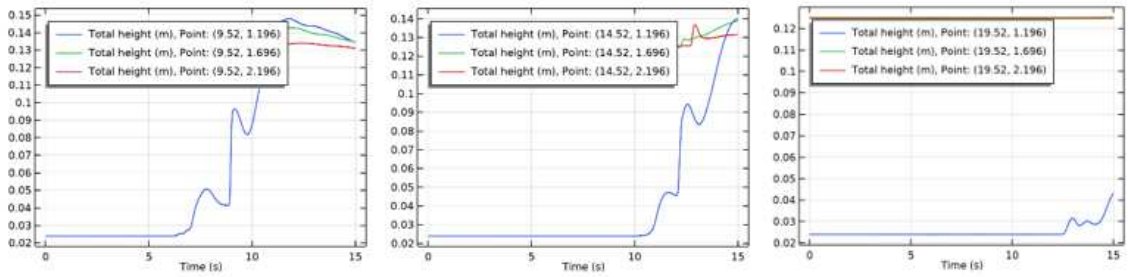

Figure 13. Stability simulation with differences 9.52 m, 14.52 m and 19.52 m wave position

From the simulation results it is shown that the difference in the distance of the breakwater that is carried out will give a difference in the value of the amplitude distribution (λ) for each position. The

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computations are carried out on an interval of 0<t<51 and show that a short distance will give a large amplitude, which means that the wave splitting does not work optimally because it gives such a large wave height value. Placement of the breakwater with a distance of 19.52 m gives a low wave height, it can be seen that the wave amplitude starts to occur at t=10 s the computation is done. The height of each wave is shown in Table 1.

Table 1. Amplitude Magnitude to variety of position.

u(x,t)	h_b=1,196	h_b=1,696	h_b=2,196
x=9,52	0.13439	0.13438	0.13097
x=14,52	0.13988	0.13859	0.13161
x=19,52	0.043203	0.12468	0.12515

Table 1 shows the magnitude of the wave height that occurs in the t(0.15) interval which gives the result that for a breakwater which is 19.52 m it gives a large wave height on the surface that is equal to 0.12515 m which is the minimum wave height value from a variation of 9 .52 m is 0.13097 m, and a distance of 14.52 m produces a wave height of 0.13161 m. To provide a difference in the computational results that have been obtained, computations will be carried out on variations in the speed of the incoming wave propagation with the assumption that the breakwater is positioned at x= 16.52 m with variations in speed, namely $v_1 = 1\frac{m}{s}$, $v_2 = 1.5\frac{m}{s}$,$v_3 = 2\frac{m}{s}$. The simulation is shown in Figure 14.

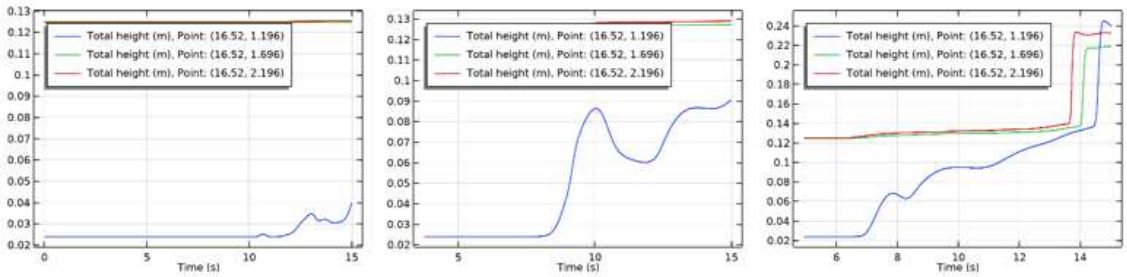

Figure 14. The difference between the change in the value of λ and the variation in the speed of the incident wave is (a) = 1 m/s, (b) = 1.5 m/s, (c) = 2 m/s

Figure 14 represents the change in amplitude that occurs due to wave breaking based on variations in propagation speed. Waves that come with v= 2 m/s give the biggest wave height, whereas v= 1 m/s produces the lowest wave height. The simulation results of wave heights for speed variations are shown in Table 2.

Table 2. Amplitude Magnitude to variety of inlet velocity.

u(x,t)	h_b=1,196	h_b=1,696	h_b=2,196
u_t =1	0.039990	0.12481	0.12538
u_t =1,5	0.090519	0.12726	0.12909
u_t =2	0.23979	0.21846	0.23229

Table 2 shows the magnitude of the wave height that occurs in the interval t (0.15] which gives the result that the incoming wave with u_t = 1 m/s gives a large wave height on the surface that is equal to 0.12538 m which is the minimum wave height value of the u_t variation = 1.5 m/s of 0.12909 m, and u_t= 2 m/s produces a wave height of 0.23229 m.

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4. Conclusions

Based on the research that has been done, it can be concluded that the simulation of wave attenuation has a significant impact on the value of the wavelength, and the magnitude of the wave propagation velocity generated by the simulation time is 15 seconds with several simulation variations, namely variations in the placement of the breakwater with a distance of 10 m , 15 m, and 20 m. the second variation of the simulation is the variation of wave velocity of 1 m/s, 1.5 m/s, and 2 m/s. The results shown are 0.12515 m respectively.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism

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