Sinkron : Jurnal dan Penelitian Teknik Informatika
Volume 8, Number 3, July 2023
DOI : https://doi.org/10.33395/sinkron.v8i3.12630
e-ISSN : 2541-2019
p-ISSN : 2541-044X

Finite Element Model of Rock Obstruction on Overtopping at the Coastline

Rony Genevent Marpaung1)*, **Tulus**2), **Mardiningsih**3)
1,2,3)Universitas Sumatera Utara, Medan, Indonesia
1)ronygenevent@gmail.com, 2)tulus@usu.ac.id, 3) mardiningsih.math@gmail.com

Submitted : Jul 1, 2023 | **Accepted** : Jul 2, 2023 | **Published** : Jul 3, 2023

Abstract: Wave overtopping is a common phenomenon that occurs during extreme sea conditions, where water waves travel over the surface of an open structure towards the sea and pass over its crest. To prevent flooding and coastal erosion, rock structures are often constructed as wave barriers along the shore. These barriers serve as a solution to mitigate wave overtopping. One of the key factors influencing overtopping is the arrival of continuous and sufficiently high-water waves that can pass through the top of coastal defense structures. Several phase settlement methods have been developed and applied to analyze wave overtopping using the Navier-Stokes (NS) equation. By employing the finite element method, numerical solutions and simulations are sought by inputting specific parameter values. This process aims to validate the accuracy of the resulting mathematical model. To accomplish this, a program is developed based on the discretization of the model, enabling a system analysis approach. The obtained results exhibit minimal error values, thereby demonstrating optimal outcomes in terms of rock placement. The entire fluid mechanics system analysis is simulated using the COMSOL Multiphysics 5.6 program, which provides a comprehensive platform for studying and evaluating the performance of the wave barrier system.

Keywords: Finite Element Method, Overtopping, Rock, Coastline

INTRODUCTION

The interaction between waves and coastal structures has long been a subject of extensive research due to its profound implications for coastal engineering and management. In particular, overtopping, the phenomenon where waves spill over the crest of coastal structures, poses a significant challenge for coastal protection and flood risk assessment (Wang, 2018). Understanding the underlying mechanisms and accurately predicting the effects of wave overtopping is crucial for designing resilient coastal defenses.

Among the factors influencing wave overtopping, the presence of rock obstructions near the coastline has gained considerable attention. These obstructions, such as natural or placed boulders, alter wave dynamics and have the potential to reduce wave overtopping volumes, thus enhancing the resilience of coastal structures (Takagi et al., 2020). However, comprehensively assessing the effectiveness of rock obstructions and optimizing their design requires advanced numerical modeling techniques capable of simulating complex fluid-structure interactions.

Finite Element Method (FEM) has emerged as a powerful tool for analyzing such intricate phenomena. FEM discretizes the domain into smaller elements, allowing for a detailed representation of the physical system and capturing localized interactions (Marijnissen et al., 2021). One widely used software

name of corresponding author

package for implementing FEM is COMSOL Multiphysics, which offers a flexible and versatile environment for simulating and analyzing complex Multiphysics problems.

This article presents a finite element model developed using COMSOL software to investigate the effects of rock obstructions on wave overtopping at the coastline (van Gent et al., 2022). By utilizing COMSOL's capabilities, the model considers various factors such as wave characteristics, rock geometry, and coastal topography to simulate the wave-overtopping process accurately. Overall, this study aims to contribute to the understanding of wave overtopping at the coastline and provide a reliable and efficient numerical tool for evaluating the effectiveness of rock obstructions (H.-P. Chen & Mehrabani, 2019). By leveraging the capabilities of COMSOL software, a comprehensive assessment of wave overtopping dynamics in the presence of rock obstructions can be achieved, supporting informed decision-making in coastal engineering and management practices.

LITERATURE REVIEW

Excessive seawater runoff can cause abrasion, namely the erosion of land and buildings in coastal areas due to destructive ocean waves and currents. This could result in damage or collapse of the building. Therefore, a breakwater structure is needed to prevent the entry of sea water into the land caused by sea waves. The embankment that is built is often a breakwater structure by having a revetment surface consisting of tightly packed concrete blocks and augmented by piles of large stones as a breakwater. All of these types of dikes require protection against direct wave erosion, which is usually done by using a sea-facing revetment (Altomare et al., 2021). Even though coastal protection structures such as breakwaters have been built, it does not mean that it is impossible for sea water to enter the land. Water that overtopping through the coastal defenses is also known as overtopping.

OVERTOPPING

Wave overtopping is influenced by several parameters' characteristic of sea conditions and the geometry of the structure and the shoreline. Wave height (H), period (T), steepness (s) and water depth (h) at the toe of the structure are the main parameters to be considered when analyzing the influence of sea conditions on runoff. The geometrical parameters of the structure, such as the seashore, the slope of the embankment and piles of boulders that can block seawater are also important when studying wave overflow (Capel, 2015; Hofland et al., 2017). Since then, various formulas have been developed to predict the overflow on a debris pile breakwater which can be rewritten as follows:

$$\frac{q}{\sqrt{g_{m_0}^{3}}} = \alpha \exp\left[-\frac{\beta}{\gamma}\left(\frac{R_c}{H_{m_0}}\right)^{c}\right] \tag{1}$$

where:

q : average overtopping of waves $\left(\frac{m^3}{\frac{s}{m}}\right)$
g : acceleration due to gravity $(\frac{m}{s^2})$
R_c : the height of the sea wall relative to the shallow water level (m)
H_{m_0} : $(H_{m0} = 4\sqrt{m_0}$ significant wave height of the incident wave at the end of the structure $H_s = H_{m0}\ (m)$
γ : shows the minus effect factor for effects such as the roughness effect γf and the skewed wave effect γb
a,b,c: coefficients

STONE PILE STRUCTURE

Rock pile structures, also known as rock revetments or rock groins, are commonly employed as coastal protection measures to mitigate erosion and enhance shoreline stability. These structures consist of strategically placed rocks or boulders along the beach, forming a permeable barrier that dissipates wave energy and reduces the impact of coastal processes (Tulus, Sefnides, et al., 2018). This literature review provides an overview of the existing research on rock pile structures, focusing on their design, effectiveness, and ecological implications.

One of the coastal protection structures is to make piles or layers of excavated rock piles, protected by rock protection units. The outer armor layer is designed to withstand wave action without significant displacement of the armor unit. A layer of quarry bottom or crushed stone supports the armor and separates it from the finer material in the embankments or piles. This porous and inclined layer dissipates some of the incident wave energy in breaking and friction. A simplified form of rock piles can be used for protection sea walls in vertical walls or revetments. Rock pile revetments can also be used to protect embankments formed from sand and cement. These rock pile structures tend to be more common in areas where harder rock is available (Van Bergeijk et al., 2022).

Rock pile structures have proven to be effective coastal protection measures, providing erosion control and wave energy dissipation benefits. Optimizing their design, understanding their impact on sediment transport, and considering ecological implications are key areas of ongoing research. Further studies integrating field measurements, numerical modeling, and ecological assessments are necessary to enhance our understanding of rock pile structures and inform their sustainable implementation along coastal environments.

GENERAL WAVE EQUATION

The first equation that describes the motion of an incompressible fluid flow is the equation of the conservation of mass (Esteban et al., 2022):

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{2}$$

In addition, the momentum conservation equation in the Reynolds Averaged Navier-Stokes (RANS) form is applied to account for turbulence effects, where the velocity components are separated into averaged components and fluctuate and are averaged over time. This process introduces an additional Reynolds-stress tensor $\rho\, u_i', u_j'$ in the momentum equation to model in terms of the average flow characteristic is:

$$\frac{\partial U_i}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = \frac{1}{\rho}\,\frac{\partial}{\partial x_j} - (\rho \partial_{ij} + 2\mu S_{ij} - \rho(\, u_i', u_j' + F_i + S_i) \tag{3}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_j}\right) \tag{4}$$

where $i, j \ = \ 1{,}2{,}3$ are three spatial dimensions, U_i is the i-time average velocity component, u_i' is the fluctuating velocity component, ρ is the fluid density, S_{ij} is the viscous stress tensor and ∂_{ij} is the Kronecker delta function. ρ stands for pressure, F_i is the i^th^ component of the external field force per unit mass. The acceleration due to gravity in this particular case and S_i represents the possible source or sinking of the i^th^ component of momentum.

Based on the wave equation that is widely applied to solve energy problems, the water wave equation is applied by choosing a momentum balance problem which can be written as:

$$\frac{\partial \boldsymbol{M}}{\partial t} + \nabla T = \frac{\tau^w}{\rho_w g} \tag{5}$$

where $\boldsymbol{M} = [M_x, M_y]^T$ is a momentum vector, ∇T is the wave momentum variable at pressure flux, τ^w is the vector value of wind stress, ρ_w is the density of water and g is the value of the acceleration due to gravity. Based on research from [12], the equipartition assumption of the problem of kinetic and potential energy in waves is written as:

$$M_x = \int_{\infty}^{0} \int_{2\pi}^{0} \frac{F(f,0)}{C_p(f)} \cos\theta \ d\theta \, df \tag{5}$$

$$M_y = \int_{0}^{\infty} \int_{0}^{2\pi} \frac{F(f,0)}{C_p(f)} \cos\theta \ d\theta \, df \tag{6}$$

where the value of C_p is a wave in phase with velocity, and F is a 2-dimensional wave spectrum at frequency f and space direction θ. Then the relationship between the velocity, C_p, towards the peak frequency f_p using the linear wave equation in deep water is:

$$c_p = \frac{g}{2\pi f_p} \tag{7}$$

FINITE ELEMENT METHOD

Finite Element Method (FEM) has emerged as a valuable numerical tool for simulating complex fluid-structure interactions in coastal engineering (W. Chen et al., 2022). The method used in numerical calculations is the finite element method. The finite element method is one of the numerical methods that can be used to solve structural problems. In this method all complex problems such as shape variations, boundary conditions and loads are solved by approximation methods. The finite element procedure reduces the unknown variable to a finite number by dividing the solution area into subsets called elements and expressed as the unknown field variables in terms of approximation functions/interpolation functions/shape functions within each element.

FEM has been extensively utilized to investigate wave-overtopping phenomena and evaluate the performance of coastal structures. Studies by (Hasanpour et al., 2021; Zheng et al., 2018) employed FEM to simulate wave transformation, wave-structure interaction, and wave overtopping processes. These studies demonstrated the ability of FEM to capture the complex hydrodynamic behavior near the coastline and provided valuable insights into wave overtopping characteristics. To optimize the design of rock obstructions and maximize their effectiveness in reducing wave overtopping, sensitivity analyses and optimization techniques have been employed in FEM studies. For example, (Latham et al., 2009) conducted a sensitivity analysis using FEM to evaluate the influence of different rock groin configurations on wave overtopping reduction. The study identified the optimal dimensions and spacing of rock groins for minimizing wave overtopping volumes.

METHOD

To illustrate the first step of defining the problem and establishing objectives in developing a finite element model for the study of rock obstruction on wave overtopping. As a first step to building a breakwater model, a rock pile database has been designed with various geometries. Numerical reconstruction of the breakwater originating from the rock structure will be tested and simulated using the COMSOL program. Depth to sea level has been defined in the COMSOL program, whereas the distance of height and slope of a wave defense comes from the source of the development of a paper on overtopping that allows proper interaction with the incident wave. The following data can be used in the formation of a coastal defense model using a layer rock structure in COMSOL:

1. Structure Geometry:
   - Dimensions: Height = 5 meters, Width = 10 meters, Depth = 2 meters.
   - Rock Pile Configuration: The rock pile is pyramid-shaped with specific height and slope angles.

2. Material Properties:
   - Rock Density: 2500 kg/m^3.
   - Rock Strength: Compressive strength of 20 MPa.
   - Surface Roughness: Roughness coefficient = 0.05.
   - Porosity: 35%.
   - Permeability: 1.5 x 10^-5 m/s.
3. Boundary Conditions:
   - Incoming Waves: Waves with a specific energy spectrum and incoming direction.
   - Tides: Tidal height varies according to the local tidal schedule.
   - Current: Horizontal current with a velocity of 0.5 m/s in a specific direction.
   - Wind: Wind with a velocity of 10 m/s blowing towards land.
4. Hydrodynamic Properties:
   - Wave Velocity: 3 m/s.
   - Wave Period: 8 seconds.
   - Wave Incidence Angle: 45 degrees with respect to the x-axis.
5. Solver Settings:
   - Numerical Method: Finite Element Method.
   - Time Step Size: 0.1 seconds.
   - Solver Convergence: Convergence tolerance of 1e-6.
   - Simulation Domain: The simulation domain includes the area around the rock structure

This data will be used in COMSOL to build mathematical models, enter these parameters and conditions, and perform numerical simulations that describe the behavior of rock structures against ocean waves. So that the model created will form like in this image in COMSOL

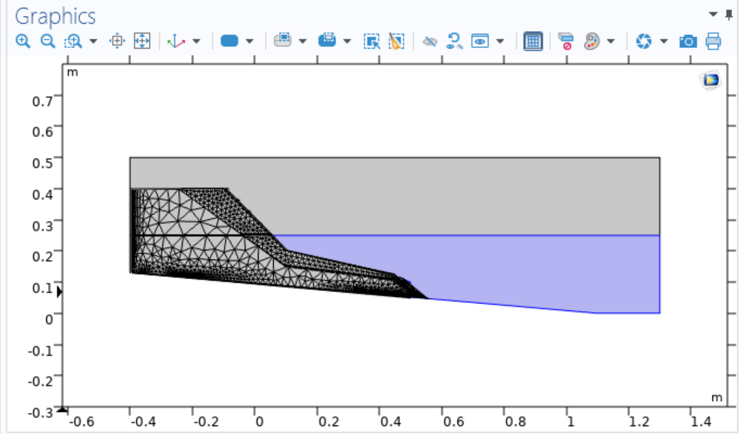

Fig 1. Stone Pile Structure

Furthermore, to analyze the drag on the rock structure, the finite element method is used with numerical solutions and simulation using the specified parameter values. This is done to test the validity of the resulting mathematical model. For this purpose, it is necessary to build a program that produces model discretization results and analyzes the systems approach. Thus, results are obtained which have a very small error rate and can prove optimal results in the design of rock structures. Accurate numerical simulation of waves overflowing over the crest of a structure requires adequate numerical treatment of all relevant physical processes.

To predict the fluid velocity and pressure around rocks on the coast, the following partial differential equations are used to describe fluid movement. The Navier-Stokes equations are expressed as follows (Tulus, Mardiningsih, et al., 2018):

$$\rho\left(\frac{\partial u}{\partial t}+\mu\nabla u\right)=-\nabla p+\mu\nabla^{2}u+f \tag{8}$$

$$\nabla\cdot \mathrm{u}=0 \tag{9}$$

where ρ is the fluid density, u is the fluid velocity vector, p is the fluid pressure, μ is the fluid viscosity, f is the force acting on the fluid, ∇ is the nabla operator, and $\nabla^2 u$ is the laplacian of the fluid velocity vector.

The momentum equation (8) describes the conservation of fluid momentum, stating that the change in fluid momentum within a volume must be equal to the sum of forces acting on the fluid within that volume. Furthermore, the continuity equation (9) represents the conservation of fluid mass, stating that the volume of fluid entering an area must be equal to the volume of fluid exiting that area. Hence, from these two equations, turbulent transport and turbulent kinetic energy in the fluid can be formed, where k represents turbulent kinetic energy, and ϵ represents the rate of turbulent dissipation.

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho k u) = \nabla \cdot (\mu\, e f f\, \nabla k) + Pk - \epsilon$$
$$\frac{\partial(\rho\epsilon)}{\partial t} + \nabla \cdot (\rho\epsilon u) = \nabla \cdot (\mu\, e f f\, \nabla\epsilon) + C1\epsilon\left(\frac{\epsilon}{k}\right) - C2\epsilon\left(\frac{\epsilon}{k}\right)^{0.5} \tag{10}$$

Thus, equations 8, 9 and 10 will be used in fluid modeling to predict fluid movement around rocks on the coast and other locations. This fluid modeling can be used to understand fluid behavior and design structures resistant to fluid pressure, such as seawalls or coastal barriers.

The COMSOL program is already based on the Navier-Stokes equation which uses the shallow water flow method to view the free surface. So, the general Navier-Stokes equation can explain this flow process (Tulus et al., 2019) [18]:

$$\frac{\partial ui}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\frac{\partial^2 u_i}{\partial x_j} \tag{11}$$

the equation after this statement v is the molecular viscosity, u_i is the i variable component from time to time and ρ the instantaneous effective pressure and g_i the x_i variable component for the gravitational force. Various models of turbulence are available. On the issue of coastal hydrodynamics, the COMSOL program has been well tested.

RESULT

In this section, plots are created using the plot function in COMSOL. The x-axis represents the slope angle of the rocks in degrees, while the y-axis represents the drag force in kN/m. The plot title indicates the input parameters used in the model.

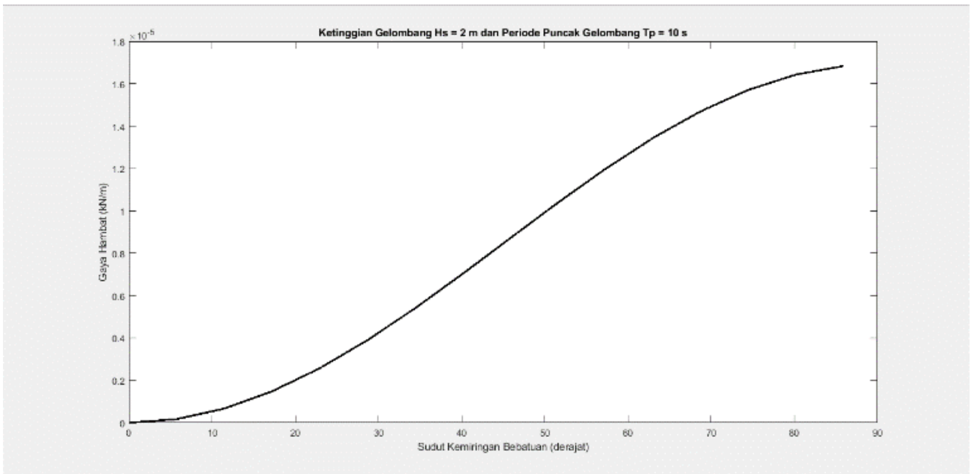

Fig 2. Slope Angle of Coastal Rock Structure

In the plot, it can be observed that the drag force on the rocks reaches its maximum at an approximate slope angle of 45 degrees. As the slope angle decreases, the drag force experienced by the rocks decreases as well. This plot can be used to calculate the drag force under various different sea conditions and can be utilized in the planning of coastal structures such as seawalls or jetties.

In overtopping analysis, the height of the sea waves is used as a parameter to predict the amount of seawater that may overflow through coastal defense structures, such as seawalls or breakwaters. The higher the sea wave, the greater the likelihood of overtopping. In this case, data on the height of the sea waves can be used to calculate parameters such as significant wave height, dominant wave period, or other relevant characteristics in overtopping analysis. Here is the plot generated by the program in calculating the random sea water level.

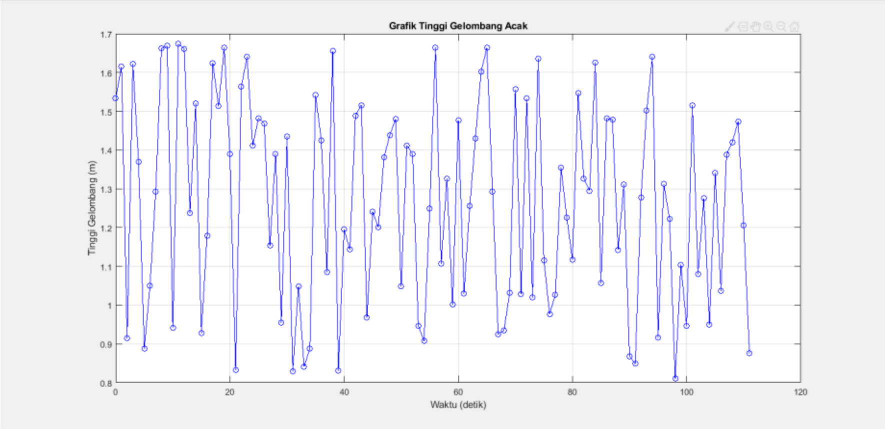

Fig 3. Random Wave Height

Next, a model will be generated to calculate the drag force on coastal protection structures with varying widths along the coastline. This model is based on parameters such as significant wave height (Hs), peak wave period (Tp), dominant sand grain size (d50), seawater density (ρw), rock density (ρs), drag coefficient (Cd), scale factor alpha, number of points on the coastline (N), coastline length (L), height of the coastal protection wall (h), and slope angle of the rocks (θ).

In this model, these parameters are used to calculate the drag force acting on the coastal protection wall due to the presence of ocean waves. Firstly, these parameters are used to calculate beta, which is a coefficient associated with these parameters. The width of the coastline (b) is then calculated based on the scale factor alpha and the position on the coastline (x). Subsequently, the slope angle of the rocks (θ) is calculated based on the height of the coastal protection wall (h) and the width of the coastline (b). Following that, the drag force on the rocks (Fh) is calculated based on the slope angle of the rocks (θ) and the beta coefficient. The results of this model are then plotted on a graph, with the x-axis representing the position on the coastline (m) and the y-axis representing the drag force (kN/m).

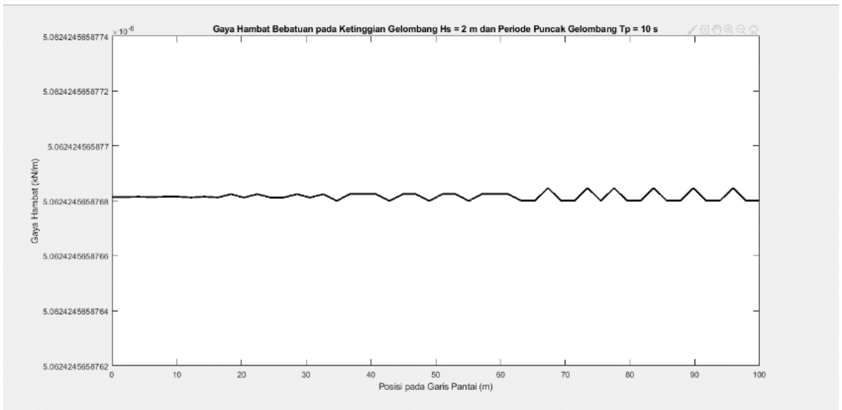

Fig 4. Rock Resistance Force

From this model, the drag force is calculated at each point based on the sea water level above the seabed, seawater density, rock density, and drag force scale factor. The upper and lower limits of the drag force are set as 0.2 and 0, respectively. Then, the simulation results are plotted in the form of a two-dimensional image, which shows the sea water level and drag force at each point.

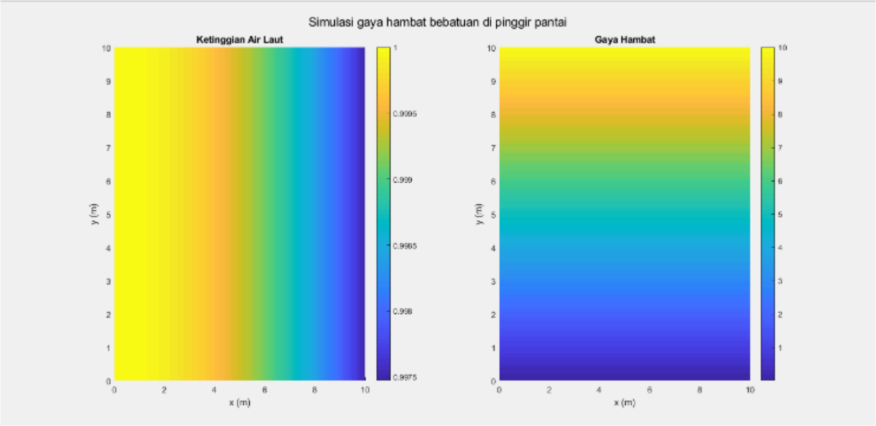

Fig 5. Simulating the drag of the rock layers

For the numerical simulation of fluid flow through a 2D rock field, the rocks are located at the center of coordinates and the rock surface is defined by the function h(x, y). At each time iteration, the program calculates the wave height and water velocity to determine the horizontal water velocity above the rocks. The program then computes the drag force at each point on the rock surface using Newton's drag law. The water discharge passing through the rocks is calculated as the sum of drag forces on each side of the rocks. The program also calculates the changes in velocity and position of the rocks at each time iteration using Newton's equations of motion. During the simulation, the program plots the rock surface and flow every 100 time iterations using the surf and quiver functions. These plots provide a visual depiction of how the flow passes through the rocks in the 2D field.

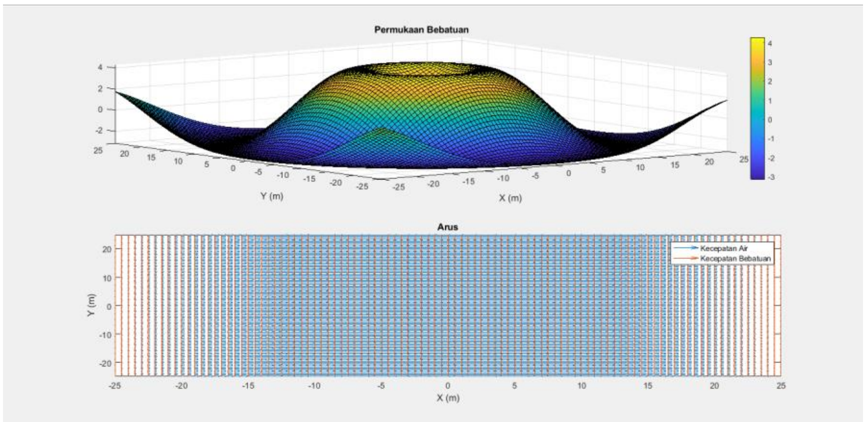

Fig 6. Numerical simulation of fluid flow on rock surfaces

Next, a graph will be shown depicting the variation of wave overtopping discharge over the measurement time. Wave overtopping discharge is the average discharge per linear meter with a width, q, for example, in m³/s per m. In the graph, the data points of the overtopping discharge (indicated by blue markers) and the red dashed line representing the average discharge can be observed. This graph provides a visualization to observe the pattern of wave overtopping discharge within the given time range.

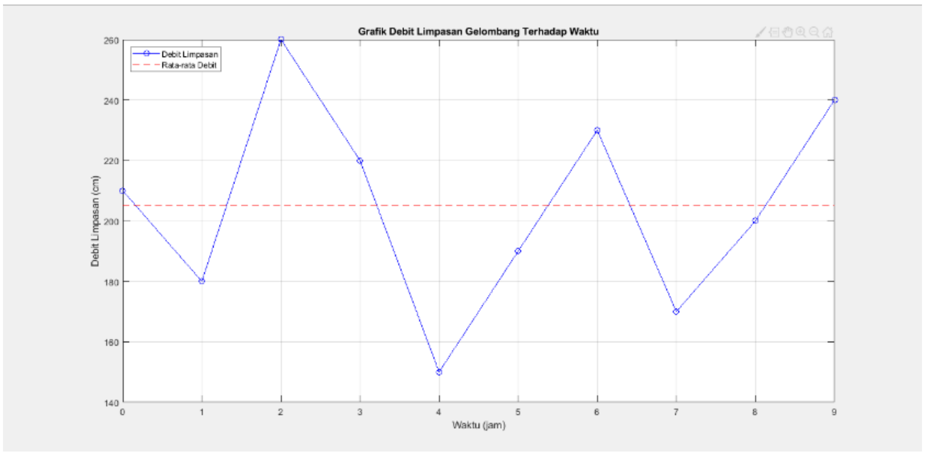

Fig 7. Wave overflow discharge against time

In the first part, there are settings for the measurement time parameter, t, in hours, and the height of the sea wave, Hs, in meters. This data is used as input to calculate the wave overtopping discharge. Next, the wave overtopping discharge is calculated by multiplying the wave height, Hs, by the conversion factor of 100 to change the unit from meters to centimeters. The result is stored in the variable "debit" (discharge). After that, the average discharge (average debit) is calculated using the mean function on the discharge data. Next, a graph of the significant wave height H_{m0} for the given geometry will be displayed.

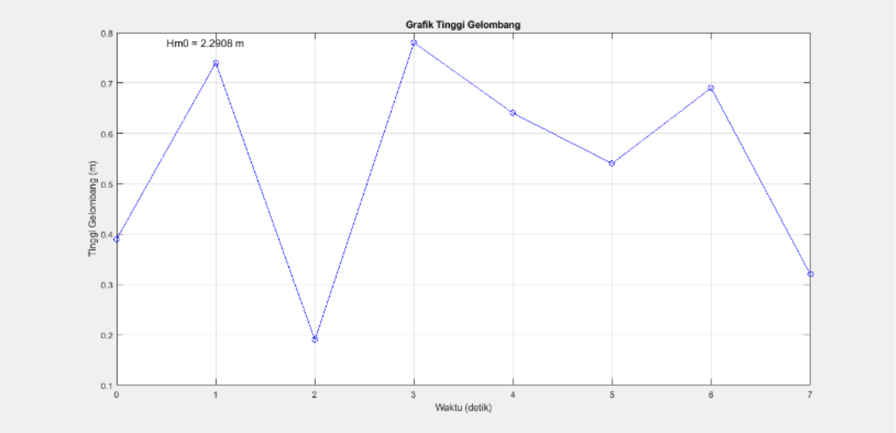

Fig 8. The result of the layer geometry

These results look at how the conditions of the waves and sea walls overtopping and the iteration conditions with two trials.

Table 1. Wave Conditions and Water Level Before and After Hitting the Breakwater

Wave Conditions and Water Height	**Trial**	
	1	**2**
$H_{m0}(m)$	2.65	2.86
	2.29	2.58
$T_{m-1,0}(s)$	7.29	7.01
	7.66	7.60
$SW(m)$	3.13	2.62
	2.33	2.60

name of corresponding author

DISCUSSIONS

The data provides information on the height of the sea wave and the change in water level after the sea wave hits the seawall under various conditions. In the first experimental geometry, the height of the sea wave before hitting the seawall was 2.65 meters, which then decreased to 2.29 meters after hitting the seawall. The tidal period of the sea wave was 7.29 seconds, and during high tide, the recorded time was 7.66 seconds. The shallow water level before the sea wave hit the seawall was 3.13 meters, which decreased to 2.33 meters after the sea wave hit the seawall. Moving on to the second experimental geometry, the height of the sea wave before hitting the seawall was 2.86 meters, which then decreased to 2.58 meters after hitting the seawall. The tidal period of the sea wave was 7.01 seconds, and during high tide, the recorded time was 7.60 seconds. The shallow water level before the sea wave hit the seawall was 2.62 meters, which decreased to 2.60 meters after the sea wave hit the seawall.

With this table, we can observe the changes in wave conditions and water levels before and after they hit the wave breakers. The data provides insights into the significant wave height, dominant wave period, and sea surface height that occur in specific situations. The results of this research provide an understanding of wave conditions and changes in water levels before and after sea waves hit the seawall. This data can be used as a reference in designing effective coastal defense structures to reduce the risk of overtopping and protect coastal environments and communities from flooding and damage caused by wave surges.

CONCLUSION

The results of the developed numerical approach using a finite element-based numerical model can predict the level of overtopping that occurs on coastal defense structures attacked by waves. By utilizing accurate computational analysis, this research can provide reliable estimates of the potential amount and level of overtopping. This significantly contributes to evaluating the effectiveness of existing defense structures and designing more effective solutions to reduce the risk of overtopping. The approach differs from traditional methods as it incorporates the flow of water penetrating the seawall from the porous rock media into the flow simulation. The constructed structure is modeled with stacked rocks as coastal protection. By comprehensively analyzing the rock structure, this research provides information on the optimal shape, size, and layout of the rocks in facing high sea waves.

ACKNOWLEDGMENT

We thanks to research for Kementerian Riset dan Teknologi for funding this research with the Penelitian Tesis Magister scheme, contract number 21/UN5.2.3.1/PPM/KP-DRTPM/TI/2022 and research institution of Universitas Sumatera Utara

REFERENCES

Altomare, C., Gironella, X., & Crespo, A. J. C. (2021). Simulation of random wave overtopping by a WCSPH model. *Applied Ocean Research*, *116*, 102888.

Capel, A. (2015). Wave run-up and overtopping reduction by block revetments with enhanced roughness. *Coastal Engineering*, *104*, 76–92.

Chen, H.-P., & Mehrabani, M. B. (2019). Lifetime wave overtopping risk analysis of sea defences subjected to changing operational conditions. *Engineering Failure Analysis*, *97*, 464–479.

Chen, W., Warmink, J. J., Van Gent, M. R. A., & Hulscher, S. (2022). Numerical investigation of the effects of roughness, a berm and oblique waves on wave overtopping processes at dikes. *Applied Ocean Research*, *118*, 102971.

Esteban, G. A., Aristondo, A., Izquierdo, U., Blanco, J. M., & Pérez-Morán, G. (2022). Experimental analysis and numerical simulation of wave overtopping on a fixed vertical cylinder under regular waves. *Coastal Engineering*, *173*, 104097.

Hasanpour, A., Istrati, D., & Buckle, I. (2021). Coupled SPH–FEM modeling of tsunami-borne large debris flow and impact on coastal structures. *Journal of Marine Science and Engineering*, *9*(10), 1068.

Hofland, B., Chen, X., Altomare, C., & Oosterlo, P. (2017). Prediction formula for the spectral wave period Tm-1, 0 on mildly sloping shallow foreshores. *Coastal Engineering*, *123*, 21–28.

Latham, J.-P., Mindel, J., Guises, R., Garcia, X., Xiang, J., Pain, C., & Munjiza, A. (2009). Coupled FEM-DEM and CFD for coastal structures: application to armour stability and breakage. In *Coastal Structures 2007: (In 2 Volumes)* (pp. 1453–1464). World Scientific.

Marijnissen, R. J. C., Kok, M., Kroeze, C., & van Loon-Steensma, J. M. (2021). Flood risk reduction by parallel flood defences–Case-study of a coastal multifunctional flood protection zone. *Coastal Engineering*, *167*, 103903.

Takagi, H., Tomiyasu, R., Oyake, T., Araki, T., Mori, K., Matsubara, Y., Ninomiya, Y., & Takata, Y. (2020). Tsunami intrusion through port breakwaters enclosed with self-elevating seawalls. *Ocean Engineering*, *199*, 107028.

Tulus, Khairani, C., Marpaung, T. J., & Suriati. (2019). Computational analysis of fluid behaviour around airfoil with Navier-Stokes equation. *Journal of Physics: Conference Series*, *1376*(1), 12003.

Tulus, Mardiningsih, Sawaluddin, Sitompul, O. S., & Ihsan, A. K. A. M. (2018). Shear rate analysis of water dynamic in the continuous stirred tank. *IOP Conference Series: Materials Science and Engineering*, *308*(1), 12048.

Tulus, Sefnides, I. Z., Sawaluddin, Suriati, & Dwiastuti, M. (2018). Modeling of sedimentation process in water. *Journal of Physics: Conference Series*, *978*(1), 12080.

Van Bergeijk, V. M., Warmink, J. J., & Hulscher, S. J. M. H. (2022). The wave overtopping load on landward slopes of grass-covered flood defences: Deriving practical formulations using a numerical model. *Coastal Engineering*, *171*, 104047.

van Gent, M. R. A., Wolters, G., & Capel, A. (2022). Wave overtopping discharges at rubble mound breakwaters including effects of a crest wall and a berm. *Coastal Engineering*, *176*, 104151.

Wang, Y. (2018). Transformed Rayleigh distribution of trough depths for stochastic ocean waves. *Coastal Engineering*, *133*, 106–112.

Zheng, H., Shioya, R., & Mitsume, N. (2018). Large-scale parallel simulation of coastal structures loaded by tsunami wave using FEM and MPS Method. *Journal of Advanced Simulation in Science and Engineering*, *5*(1), 1–16.