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EVALUATION OF COASTAL SAFETY STRUCTURES IN MITIGATING WAVE OVERTOPPING: A LABORATORY SIMULATION APPROACH

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Abstract

This research evaluates the performance of coastal safety structures in mitigating wave runoff through laboratory-scale simulations. Pancana Beach in Barru Regency, South Sulawesi, was selected as the research site due to its vulnerability to wave-induced beach damage. To simulate wave conditions, a wave generator was designed using a 12-volt DC motor integrated into an acrylic wave bath. This research analyses the effectiveness of three types of coastal safety structures: reflectors, sea walls and sloping sea walls. Laboratory experiments measured the wave overflow volume for each type of structure under controlled conditions. The results showed that reflector-type structures achieved the highest efficiency in mitigating wave overtopping, with an average minimum overtopping value of 0.006 m^3/ms. The findings emphasise the importance of selecting and designing appropriate coastal protection measures to minimise coastal erosion, protect coastal infrastructure and reduce risks to surrounding settlements. This study contributes valuable insights into the role of engineered structures in enhancing coastal resilience, especially for areas vulnerable to high wave energy..

Keywords **:** *wave overtopping, coastal safety structures, laboratory simulation.*

1. INTRODUCTION

Indonesia is currently focusing on maritime development. One important aspect of maritime development is the construction of coastal protection structures as well as the preservation of marine ecosystems. Coastal communities still face four main problems that must be addressed. For this reason, the Ministry of Maritime Affairs and Fisheries (KKP) will intervene to strengthen the economy of coastal communities and village resilience through the Resilient Coastal Village Development Programme (PDPT). Minister of Maritime Affairs and

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Fisheries Sharif Cicip Sutardjo said that the four main problems faced by coastal communities are poverty levels, damage to coastal resources, low independence of village social organisations, and lack of infrastructure and environmental health in village settlements. The four main problems above contribute to the high vulnerability of villages facing natural disasters and climate change (Armono, 2018). Climate change is a result of global warming that has a negative impact on coastal areas, especially on the life activities of fishing communities. The negative impacts of climate change include erratic seasons, rising sea surface temperatures, changing rainfall patterns, extreme weather intensity, and the emergence of large waves (Rencana Kerja Pemerintah Daerah Kabupaten Barru Tahun 2023, 2023).

The administrative location of South Sulawesi Province where there are 19 out of 24 administrative areas located on the coast, it can generally be stated that the potential threat of extreme waves and abrasion is very high. Analysis of the two parameters, namely waves and wind, to determine the intensity of the threat in each district/city shows a correlation that the more open a district is, the greater the intensity of the threat. Based on the record of events to date, it can be stated that the potential threat of extreme waves has three categories, namely high, low and none, for districts / cities in South Sulawesi, the high threat potential category is Bantaeng, Barru, Bone, Bulukumba, Jeneponto, Selayar Islands, Maros, Pangkajene and Islands, Pinrang, Sinjai, Takalar, Wajo, Makassar, Palopo, Pare-pare. The low threat potential category is Luwu, North Luwu, and East Luwu and for the no threat potential category are Enrekang, Gowa, Sidrap, and Soppeng (Rencana Penanggulangan Bencana Periode 2021-2025, 2021)

Barru Regency is one of the regencies located on the west coast of South Sulawesi Province with a coastline length of 78 km and facing the Makassar Strait (Arifah et al., 2023). The purpose of this research is to find out how efficiently the coastal safety building holds overtopping waves entering Pancana beach and comparison of other forms of coastal safety buildings.

The beach is generally defined as the boundary between the land area and the ocean area. The beach is an area at the edge of the water that is influenced by the highest tide and the lowest tide. Coastal areas are often also called coastal areas or coastal areas. Coastal or coastal areas are a land and its waters where the area is still influenced both by land activities and by marine activities (Aldin et al., 2015).

Waves

Ocean waves can vary depending on the generating force. They can be wind waves (waves generated by blowing wind), tidal waves (waves generated by the force of attraction of celestial bodies, especially the force of attraction of the sun and the moon to the earth), tsunami waves (waves that occur due to volcanic eruptions or earthquakes on the seabed), small waves (usually generated by moving ships) and so on. In this case, the commonly used wave forms are wind waves and tidal waves. Waves usually generate energy to shape beaches, generate currents and transport sediment along the coast. The shape of ocean waves is very complex and difficult to describe mathematically because of its nonlinearity, three-dimensionality and random shape (Aldin et al., 2015).

Tides

Tides are fluctuations (ups and downs) of sea level due to the force of attraction of objects in the sky, especially the moon and the sun to the mass of sea water on earth. The force of attraction between the moon and the earth affects the tides more than the force of attraction between the sun and the earth, because the force of attraction of the moon to the earth is 2.2 times greater than the force of attraction of the sun to the earth. This happens because although the mass of the moon is smaller than the mass of the sun, the distance of the moon to the earth is much closer than the distance of the earth to the sun (Triatmodjo, 1999).

Definition of Coastal Protection Building

Coastal protection buildings are infrastructure that serves as a coastal protection from the influence of several factors such as tides, erosion, and so on. Coastal buildings are usually used for the benefit of tourist facilities, especially in tourist beach areas (Arifin, 2018).

Classification of Coastal Protection Buildings

Coastal damage must be resolved immediately by building coastal protection buildings so that settlements are not eroded by sea water. The alternative coastal buildings are as follows:

Sea Dikes

Sea dikes are coastal structures that serve to protect low-lying areas from flooding due to incoming sea water. Sea dikes are built of fine materials such as clay and sand formed by mounds with a gentle slope in order to reduce erosion from incoming waves. The surface of the embankment is usually grass, asphalt, rocks or reinforced concrete (Triatmodjo, 1999). Sea dates are placed parallel to the shoreline, not attached to the coastal cliff, so that between the cliff and the sea dike can be done the process of backfill, sea dike is generally rubble mound type with armour from the arrangement of empty stones or piles of concrete blocks (Muliati, 2020).

Revetment

Revetment is a coastal building that functions as a barrier to wave forces and ocean currents that cause coastal erosion. Revetment is usually built on the shoreline or land used to protect the beach from scouring waves (Herawati, 2020). The purpose of building a revetment is to protect the land directly behind the building, as well as buildings facing the direction of the waves from the vertical or oblique side. However, seawalls are often vertical walls, while revetment buildings have sloping sides. Revetments also serve to: 1) protect the coastal cliff or slope face, all of which contribute to increasing the stability of the protected shoreline or embankment shoulder, 2) protect the coastal area immediately behind the construction against the effects of waves and ocean currents. Revetments are generally of the rubble mound, riprap or blank stone masonry type (Muliati, 2020).

Seawall

According to the Circular Letter of the Minister of Public Works No. 07 / SE / M / 2010 that Seawall is a coastal safety structure built in the direction parallel to the beach with the aim of protecting the beach against wave impact and reducing runoff inundation of the beach area behind it. Seawall is a coastal building that functions to handle relatively high waves as a whole. This building is built parallel to the shoreline and limits the fields of land and sea. The building materials used are stone and concrete masonry, most of the damage to this building is caused by a less deep foundation and the presence of water flow or seepage behind the wall (Herawati, 2020). According to (Triatmodjo, 2006), the types of seawall that are commonly used include:

1) Concrete curve-face seawall is used to withstand high waves and reduce the energy of ocean waves.

2) Particular combination curve-stepped seawall is used to withstand high waves and reduce wave energy.

3) Concrete stepped seawall is used to withstand moderate waves.

4) Rubble mound seawall is used to defend the coast from hard waves.

2. RESEARCH METHOD

Time and Place of Study

This research was conducted for 8 (months) months starting from the preparation of the report to the final reporting, and was carried out at Pancana Beach, Pancana Village, Tanate Rilau District, Barru Regency as a case study for data collection.

Figure 1. Research location map

This section includes research design, data collection instruments, participants/sample, the procedure of data collection, and data analysis

Tools and Materials

Making laboratory-based simulation tools by scaling the field conditions of the research location with tools, as follows:

a. Acrylic size 5 mm thickness
b. Acrylic
c. Motor
d. Glass Glue
e. Binding wire
f. Hook wire
g. 12V/24V DC motor and fittings
h. Motor speed regulator
i. Wiper/wheel components reduction gear

The materials to make the coastal safety building prototype:

a. Cement
b. Sand
c. Water
d. Gravel
e. Wire mesh

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f. Bakisting plywood

Wave Simulation Tool Design

In designing a laboratory-scale wave simulation tool, some commonly used approaches include:

Motor-based Design Approach

DC Motor: One of the approaches used is to utilise a DC motor as the main component in the wave generation system. In this study, the speed of the DC motor was adjusted to produce different wave heights and lengths by varying the water depth and motor speed.

Props Development

Simulation Tub: In some studies, props in the form of wave ripple simulation tubs are designed to support the learning process. This tub is usually made of transparent material such as glass and is equipped with a wave lighter that uses a motor or dynamo to create waves, in this study the material used in the ripple tub is Acrylic material.

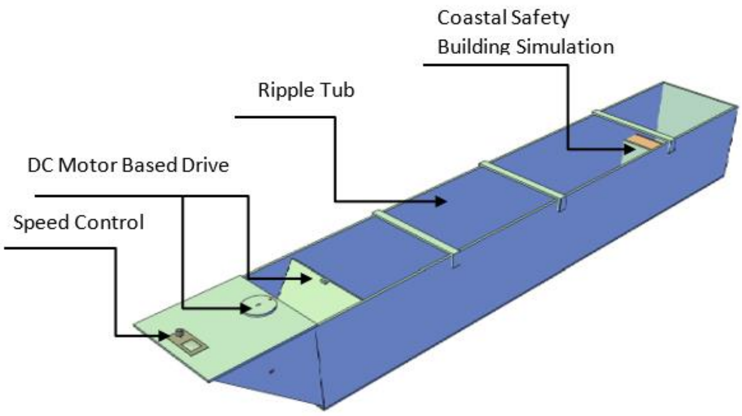

Figure 2. Wave simulation design

The wave simulation design shown in Figure 2 is 150 x 25 x 25 cm in size, with a 12-volt DC motor-based drive equipped with a speed control that can adjust the motor rotation speed from 0-100% of the DC motor voltage.

3. RESULT

Bathymetry

Bathymetry is a map that shows the relief of the seabed or seabed area as contour lines (isodepth) and depth selections (soundings), and usually also provides information on surface navigation.

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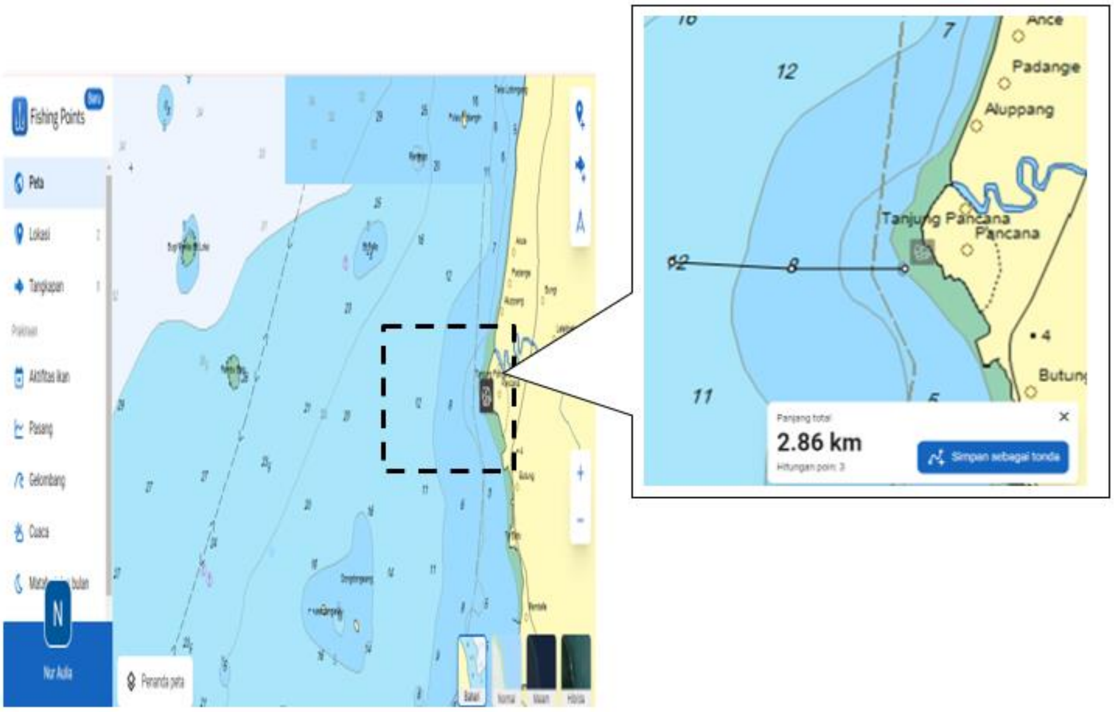

Figure 3. Depth map of the seabed in pancana coastal area

Based on the depth map around the coast of Pancana along the 2.86 km distance from the mainland to the sea has a depth of 8 m to 12 m with a slope level of 0.33º obtained from the calculation of the slope angle using trigonometric theory by utilising the length and depth of Pancana coast, it can be said that Pancana coast is included in the category of sloping beach with a slope level < 60º.

Tides

Tides are a phenomenon of periodic movements of the rise and fall of sea levels caused by a combination of gravitational and attractive forces of astronomical bodies, especially by the sun, earth and moon.

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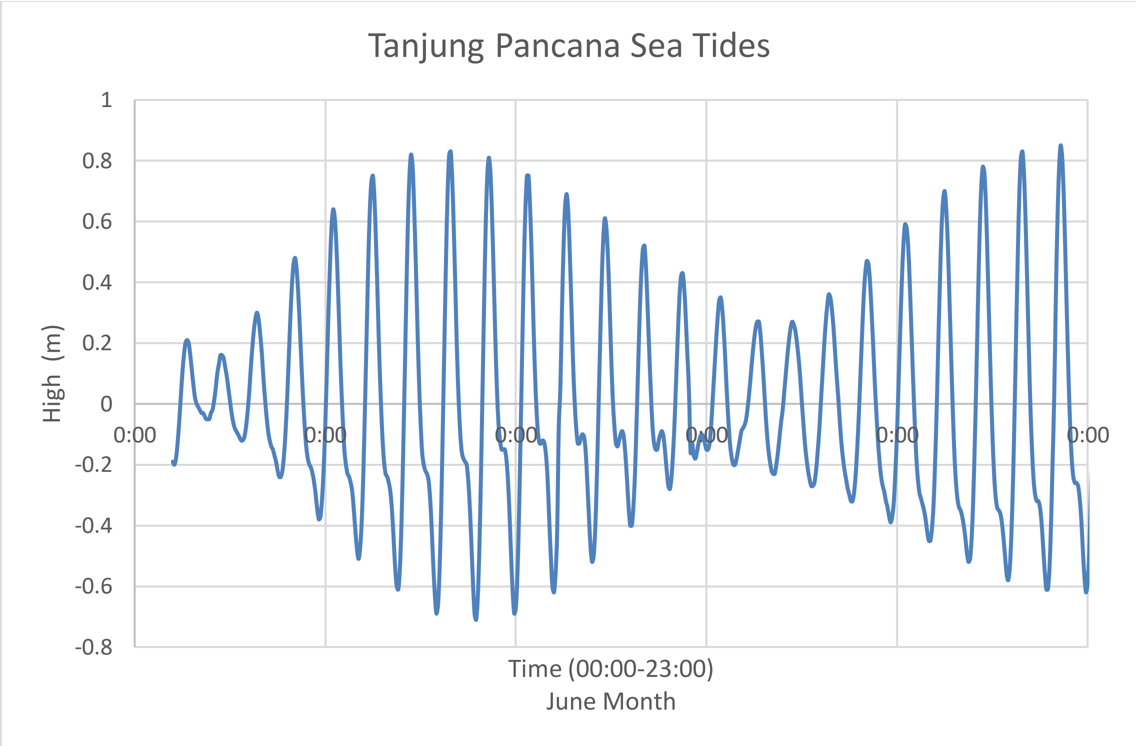

Figure 4. Tidal data results for june

Based on the results of tidal data at Tanjung Pancana, the lowest tide occurred on 08 June 2024 with a height of -0.71 m, and the highest tide occurred during the Full Moon time span on 22-24 June 2024 with a height of 0.85 m. The type of tidal variation that occurs at Tanjung Pancana is Diurnal Tide which consists of one high tide and one low tide per day. The type of tidal variation that occurs at Tanjung Pancana is a Single Daily Tide (Diurnal Tide) which consists of one high tide and one low tide in a day.

Waves

Based on wave data obtained from the fishing point application with several coordinates used in taking data for the Pancana coastal area, the average wave height is 0.2 - 0.5 m with a period of 3 seconds, the wave data can be seen in Table.1 below:

Table 1. Wave data with fishing point application

Waktu	High	Period	High	Period	High	Period	High	Period	High	Period
	m	s	m	s	m	s	m	s	m	s
	29-Sep-24		30-Sep-24		1-Oct-24		2-Oct-24		3-Oct-24	
12:00 AM	0.3	3	0.5	4	0.4	3	0.4	3	0.2	3
4:00 AM	0.4	3	0.5	3	0.4	3	0.4	3	0.2	3
8:00 AM	0.4	3	0.5	3	0.3	3	0.3	3	0.2	3

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12:00 PM	0.4	3	0.4	3	0.3	3	0.2	3	0.2	3
4:00 PM	0.4	3	0.4	3	0.3	3	0.2	3	0.3	3
8:00 PM	0.5	4	0.4	3	0.4	3	0.2	3	0.3	3
Avg.	0.4	3.2	0.5	3.2	0.4	3.0	0.3	3.0	0.2	3.0

Wave Simulation Design

Wave simulation modelling cannot be separated from the observation of the research location, namely the Pancana coast as far as 2.8 km. Pancana Beach is a sloping beach judging from the surface slope on the bathymetry map, so the design of the wave ripple tub dimensions used are 135 cm x 25 cm x 25 cm with the surface of the tub not taken into account in this case no slope is applied. For the voltage of the 12 volt DC motor, from the experiments carried out, the minimum speed that is able to drive the wave drive is at 45% and the maximum speed is 55% with a speed interval of 5%.

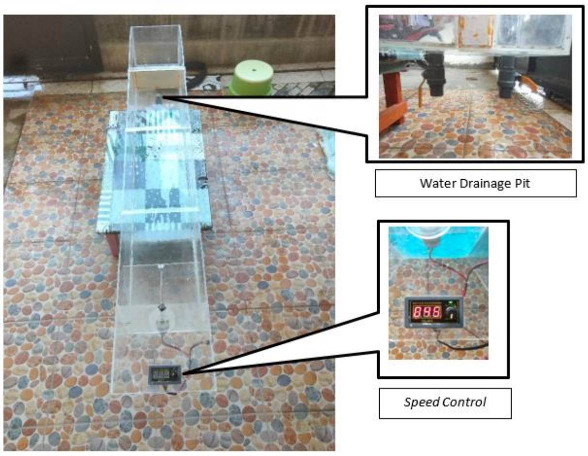

Figure 5. Laboratory-scale wave simulation

Figure 5 shows the wave simulation tool made of acrylic material with a thickness of 5 mm and given 3 anchoring points at the top to prevent sagging of the wave ripple bath.

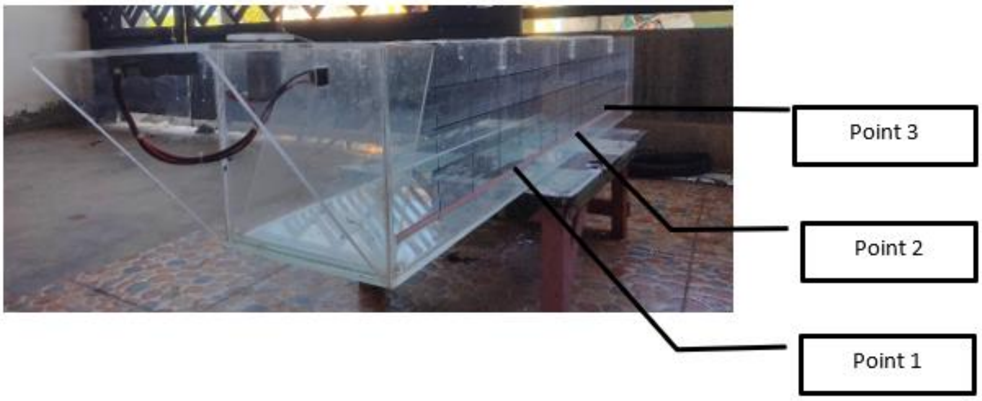

Figure 6. Measurement points in wave simulation

Table 2. Observation results of wave simulation at a depth of 15 cm

DC Motor Speed	Point 1	Point 2	Point 3	Average

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	cm	cm	cm	
45% to 1	0.5	0.5	0.7	0.6
45% to 2	0.6	0.6	0.7	0.6
45% to 3	0.5	0.7	0.7	0.6
50% to 1	0.8	0.9	1	0.9
50% to 2	1	1.2	1.2	1.1
50% to 3	1.3	1.4	1.5	1.4
55% to 1	1.7	1.9	1.9	1.8
55% to 2	1.9	1.9	2	1.9
55% to 3	1.5	1.9	2.1	1.8

Table 3. Wave simulation observation results at 12 cm depth

DC Motor Speed	Point 1	Point 2	Point 3	Average
	cm	cm	cm	
45% to 1	0.8	0.9	1	0.9
45% to 2	1	1.2	1.2	1.1
45% to 3	0.9	1	1.1	1.0
50% to 1	1.9	2.1	2.2	2.1
50% to 2	1.8	2	2.1	2.0
50% to 3	1.9	2.1	2.1	2.0
55% to 1	2.3	2.3	2.5	2.4
55% to 2	2.1	2.1	2.2	2.1
55% to 3	2.3	2.5	2.7	2.5

Based on the observations in Table 2 at a depth of 15 cm, the average wave height at 45% speed at the measurement points is 0.6 cm, the average wave height at 50% speed at the measurement points is 1.1 cm, and the average wave height at 55% speed at measurement point 1 is 1.9 cm, meaning that the DC motor speed is directly proportional to the resulting wave height.

Likewise, at a depth of 12 cm, the average wave height at 45% speed at the measurement points was 1 cm, the average wave height at 50% speed at the measurement points was 2 cm, and the average wave height at 55% speed at measurement point 1 was 2.3 cm.

Determination of the depth and speed that will be used in the analysis of the efficiency of laboratory-scale coastal safety buildings in the Pancana Beach case study is using the statistical calculation of the Root Mean Square Error (RMSE) method RMSE is one of the most frequently used methods to assess the accuracy of simulation data. It measures the difference between the value predicted by the model and the observed value, which can be seen in table 4 below:

Table 4. RMSE statistic calculation results

Water Depth in Ripple Bath	DC Motor Speed	RMSE
15 cm	45%	0.25

	50%	0.82
	55%	1.50
12 cm	45%	0.65
	50%	1.66
	55%	1.98

Y	X	(Y-X)	$(Y-X)^2$
0.6	0.4	0.2	0.03
0.6	0.4	0.2	0.05
0.6	0.3	0.3	0.11
Average			0.06
RMSE			0.25

Based on the results of the lower RMSE statistical calculation, it shows that the simulation model is more accurate in predicting sea wave observation data, and can be used to assess the accuracy of the model in further research, then the DC motor speed used in observing the beach safety building is 45% speed with a water depth of 15 cm.

Coastal Safety Building Analysis

Efforts in overcoming abrasion are to make coastal safety buildings such as revetment, seawall, groin, jetty, breakwater that can withstand seawater abrasion. Reflector is a building that is used for abrasion resistance as well as wave resistance. In this research case study using reflector buildings.

Figure 7. Reflector building in the research case study area

These reflectors are designed with curved or terraced walls capable of absorbing wave energy, reflecting it back to the sea, and preventing water from overflowing beyond the wall, thanks to the greater thickness at the bottom. From this structure, it was scaled up to laboratory scale.

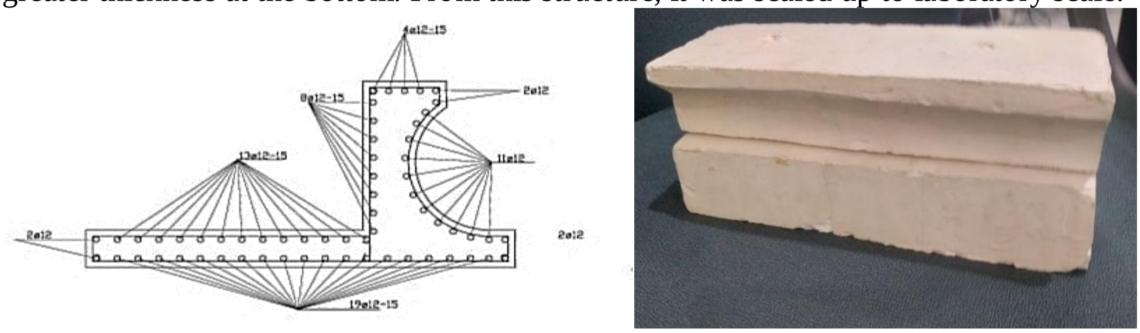

Figure 8. Laboratory-scale reflector building

In analysing the efficiency of laboratory-scale coastal safety structures using the Structure Performance Analysis approach, assessing the performance of coastal safety structures by observing how they reduce waves, control sediment, and protect the residential area behind them. This involves measuring wave height, run-up, and overtopping (Rachman, 2023). In this study, the wave height, run-up and overtopping between the reflector shore protection structure and the sea wall shore protection structure were observed, from laboratory observations, the results are shown in Table 5.

Table 5. Overtopping Analysis Result

Coastal Safety Building	Vol. run-off (ml) (Q)			t (s)	L (cm)	q = Q/L.t (m3/ms)		
	I	II	II			I	II	III
Refractor	0	5	5	7	6	0.000	0.006	0.006
Sea Dike	50	60	50	7	6	0.058	0.070	0.058
Sea Dike with Slope	70	70	80	7	26	0.019	0.019	0.022

Based on the results of the analysis of the comparison of overtopping values, it is obtained that the type of building used on the coast of Pancana Beach is very efficient, namely an average of 0.006 m3 / ms.

4. CONCLUSION

Bagian kesimpulan memuat makna hasil penelitian, jawaban atas hipotesis atau tujuan penelitian, tidak mengulang abstrak, dan kesimpulan bukan rangkuman hasil percobaan. Apabila penulis memiliki saran untuk penelitian lanjutan, maka dapat ditulis pada bagian ini. Kesimpulan disajikan dalam bentuk paragraph dengan font Times New Roman-12, Spasi 1,15.

Declaration of conflicting interest

The authors declare that there is no conflict of interest in this work.

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