Sedimentation analysis in front of a submerged rubble-mound breakwater due to daily and extreme waves simulations

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Abstract. Understanding soil dynamics in coastal structure locality is significant to evaluate the performance of coastal structures and predict the changes in coastal dynamics caused by a specific structure. Changes in sea-level can cause soil dynamic response around a submerged rubble-mound breakwater. This study analysed the sedimentation that occurred in front of the submerged rubble-mound breakwater through laboratory tests. The submerged rubble-mound breakwater was carried out with a length of 750 cm using the main protective layer of Dolos with a scale of 1:10 and the core layer using Geotube. The wave simulation used daily and extreme waves. The sedimentation research area was in front of the rubble-mound breakwater with a length of 750 cm and a width of 200 cm. The observation points were determined by dividing the research area by 50 cm in the length direction and 50 cm in the width direction. All observation points in the sedimentation study area were analysed and determined points that experienced scouring/deposition due to daily and extreme waves. The results showed that the largest scour occurred in the outer side of study area facing the incident waves, both due to simulations of daily waves and extreme waves. Further research will review the effect of sedimentation on the stability of the submerged rubble-mound breakwater.

1. Introduction

Sediments around the coastline are easily dislocated due to the influence of tides, waves, and currents, which often cause erosion on the coast [1, 2]. There are several ways that can be done to protect the coastal, namely strengthening the coast or protecting the coastal area so that it can withstand damage by constructing several coastal structures [3, 4, 5]. The rubble-mound breakwater is a coastal protection structure whose position is parallel or approximately parallel to the shoreline with the aim of reducing incident waves [6]. The purpose of the rubble-mound breakwater is to reduce wave energy (forces) behind the structure, as well as to protect the harbour pool against wave disturbances [7, 8]. In addition, it also aims to prevent coastal erosion [9, 10]. The function of the rubble-mound breakwater is to protect the harbour water pond located behind it from wave attack, some of the energy of the wave absorber will be reflected, the reduced wave energy in the protected area will reduce the delivery of sediment in the area [11].

The most common approaches for modelling sediment transport that is induced by wave–structure interactions have been done using numerical models. The advance in numerical Reynolds-Averaged Navier-Stokes (RANS) modelling was used for modelling the wave-structure interactions [12]. The numerical study on the wave-induced current and morphology changes due to the complicated interaction between waves and a sandy beach with shore-parallel breakwaters was developed based on the SWASH wave model coupled with a sediment transport [13]. The study numerically investigated the nonlinear dynamic analysis of a submerged rubble-mound low-crested breakwater constructed over a loosely deposited seabed foundation due to combined waves and currents [14]. However, there are certain aspects when developing a numerical model that needs to be studied in more detail such as the optimal boundary and the initial conditions for each numerical approach.

Experimentally, both fields and laboratory measurements focus on the structure foundation. Physical models of laboratory experiments face very severe problems with sediment and wave scale. In spite of the problems and issues that still arise in the experimental testing of the seabed response, several studies have investigated sediment transport and the scour around coastal structures. Fausset [15] compared the seabed response around rubble-mound breakwaters from field surveys to those obtained in an ocean test laboratory. On the other hand, Temel and Dogan [16] tested the time dependent investigation of the wave induced scour at the trunk section of a rubble mound breakwater.

In this study, physical models of laboratory tests were emphasized to examine the sedimentation that occurred in front of the submerged rubble-mound breakwater. The submerged rubble-mound breakwater was conducted with a length of 750 cm using dolos at the armor layer [17] and geotube (geotextile tube) at the core layer [18]. Dynamics change in sea level reflected the response of the water surface meteorological and oceanographics processes as well as tides and can be thought as periodic or episodic deviations about mean sea level. Sea level changes have an effect on the level at which wave actions occurs and may also lead to horizontal movements of water in tidal and other currents. The various reasons for sea level changes are sea level rise, i.e. increase or decrease on the amount or level of water in the ocean will create new water bodies and affect the existing landforms, and extreme events that can suddenly change (in short term) the water level in the near-shore environment and may remain permanently. The sea level rise and extreme events represent the daily and extreme waves simulations, respectively. The research area of sedimentation set in front of the rubble-mound breakwater with a length of 750 cm and a width of 200 cm. The observation points were decided by partitioning the research area of sedimentation by 50 cm in the length direction and 50 cm in the width direction. All observation points in the study area of sedimentation were examined and resolved points that are subjected to scouring/deposition due to daily waves and/or extreme waves simulation.

2. Methods

The model tests were carried out at the Laboratory of Balai Pantai, Ministry of Public Works and Public Housing of the Republic of Indonesia with a length scale of 1:10 (Froude scaling) compared to the typical prototype dimension. The wave basin is 30 m long, 10 m wide and 1.25 m deep. The model breakwater was located at the distance of 18 m from the wave generator. The regular wave generator has a length of 10 m, where the maximum wave height is 15 cm at a water depth of 50 cm and a wave period of 1.5-2.5 seconds. The wave basin configuration is shown in Figure 1.

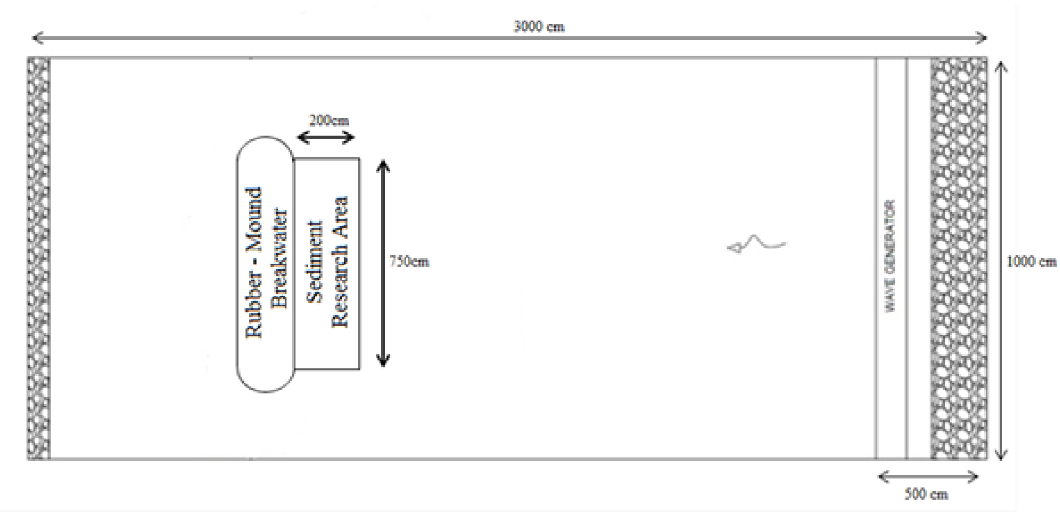


Figure 1. Wave basin configuration

Laboratory tests were focused on a submerged rubble-mound breakwater model using piles of natural stone, Geotube as the core layer and the artificial stone made of Dolos concrete as the armor layer in the direction of incident waves. The height of the rubble-mound breakwater is 42 cm. The side slope of rubble-mound breakwater facing the incident waves is 1:2.5 and the land slope of rubble-mound breakwater is 1:1.5. Figure 2 shows the process of setting up the rubble-mound breakwater model. The rubble-mound breakwater model can be seen in Figure 3.

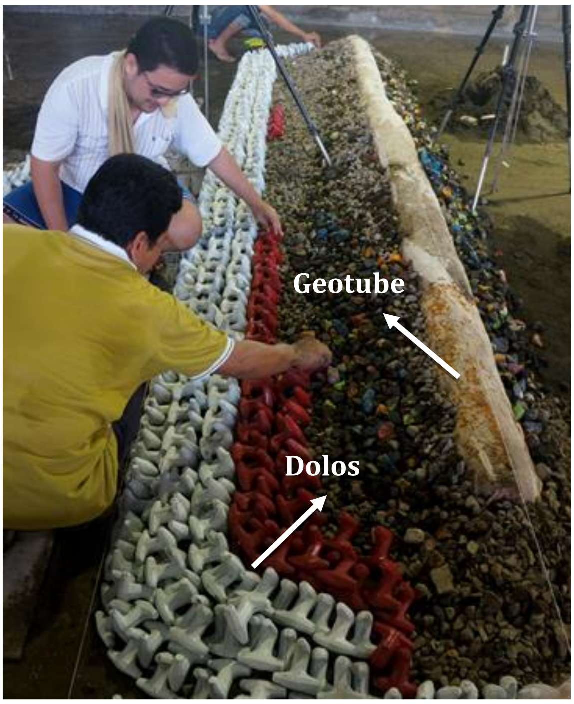


Figure 2. Process of establishing the rubble-mound breakwater model

Figure 3. Rubble-mound breakwater model

In the sedimentation test in front of the submerged rubble-mound breakwater due to daily waves simulation, the wave and water level modelling was divided into fifteen test sections. These test sections are considered the representative of the water level and wave conditions in nature as sea level rise, where tides and wave frequency changes occur; even though, each test section is only considered wave induced current. In this test, the water level was divided into five sections of 30 cm, 35 cm, 40 cm, 42 cm and 45 cm. Each water level was tested every 15 minutes (900 seconds) with three different wave frequencies, namely 10 Hz, 12 Hz and 14 Hz, respectively. The wave height and wave period were measured using wave probe located in front of rubble-mound breakwater model. The parameters of daily waves can be seen in Table 1.

Table 1. Daily waves parameters

Water Level (cm)	Time (second)	Wave Frequency (Hz)	Wave Height (cm)	Wave Period (second)
30	900	10	3.2	2.50
	900	12	2.8	2.08
	900	14	4.8	1.79
35	900	10	2.7	2.50
	900	12	4.7	2.08
	900	14	8.2	1.79
40	900	10	10.5	1.69
	900	12	4.5	1.04
	900	14	8.6	2.44
42	900	10	7.2	2.50
	900	12	5.7	2.08
	900	14	7.2	1.75
45	900	10	6.0	2.50
	900	12	6.8	2.08
	900	14	9.1	1.79

In testing of the sediment in front of the submerged rubble-mound breakwater due to extreme waves, the water level used was 45 cm and the water level was tested for a frequency of 14 Hz as the highest wave height due to daily waves simulation. This test section described the extreme event of sea level changes. The test time was 225 minutes. The parameter of the extreme wave simulation is shown in Table 2.

Table 2. Extreme waves parameters

Water Level (cm)	Time (second)	Wave Frequency (Hz)	Wave Height (cm)	Wave Period (second)
45	13,500	14	9.1	1.79

An experimental study of sedimentation using sand with the observation area was located in front of the rubble-mound breakwater on the sloping side of the direction of the incident waves. The sedimentation research area was 750 cm x 200 cm. Figure 4 presents the sedimentation research area in x- and y-directions.

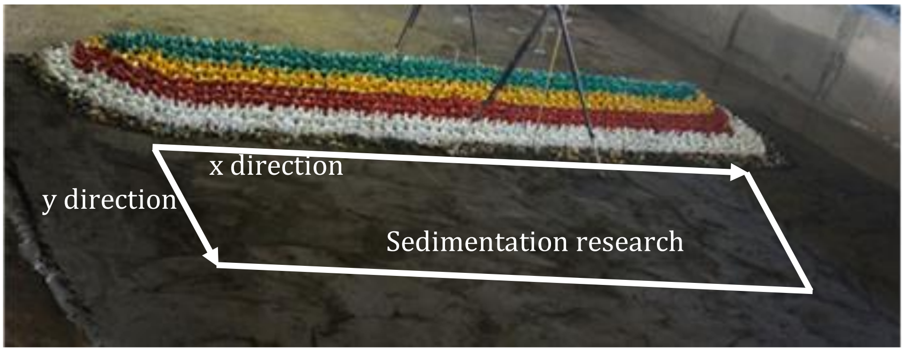


Figure 4. Sedimentation research area in x and y-directions

There were 60 research points in the horizontal direction and in the vertical direction as pointed in Figure 5. The observation points are partitioned by 50 cm in the length direction and 50 cm in the width direction. The thickness of the sand at the end of the sedimentation area in the direction of the incident waves was 2 cm and at in front of the rubble-mound breakwater was 4 cm as shown in Figure 6.

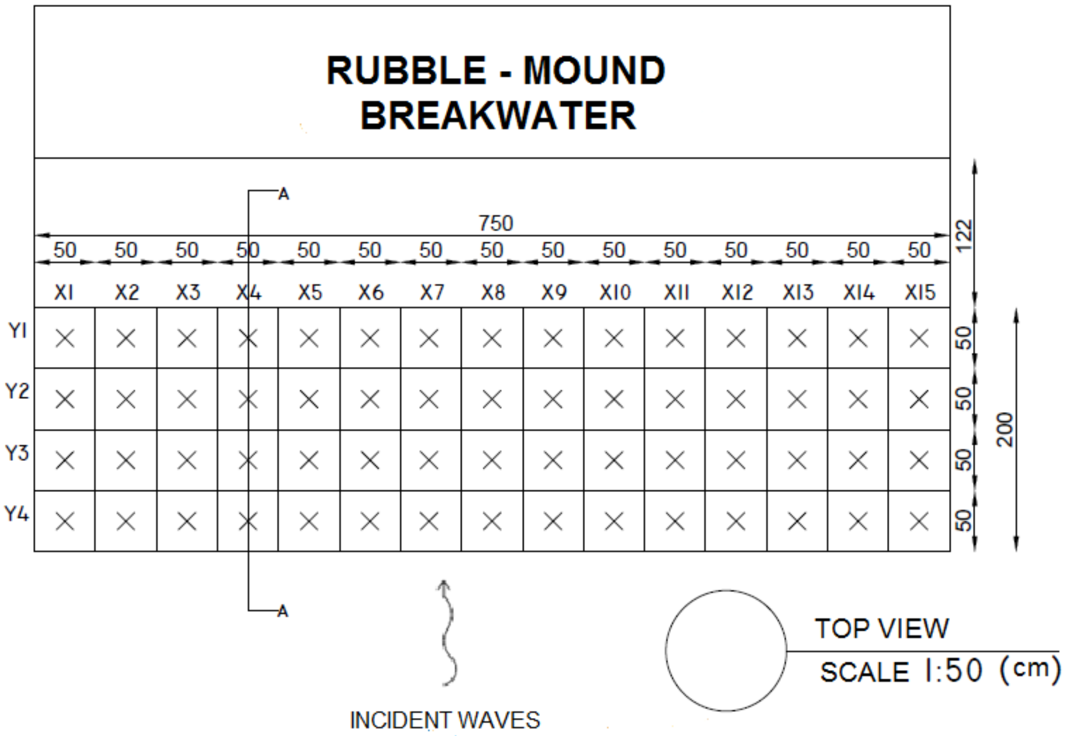


Figure 5. Sedimentation research points

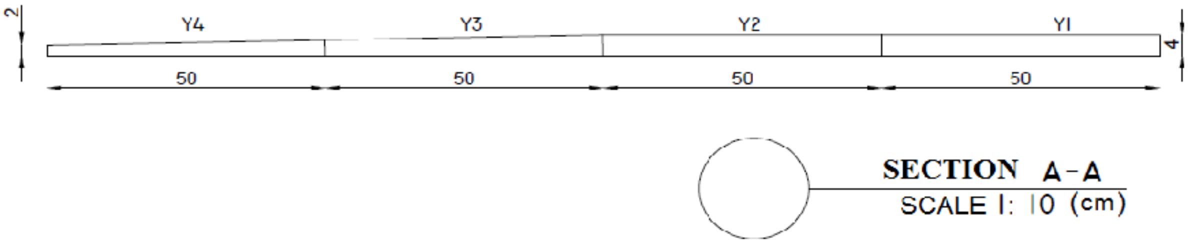
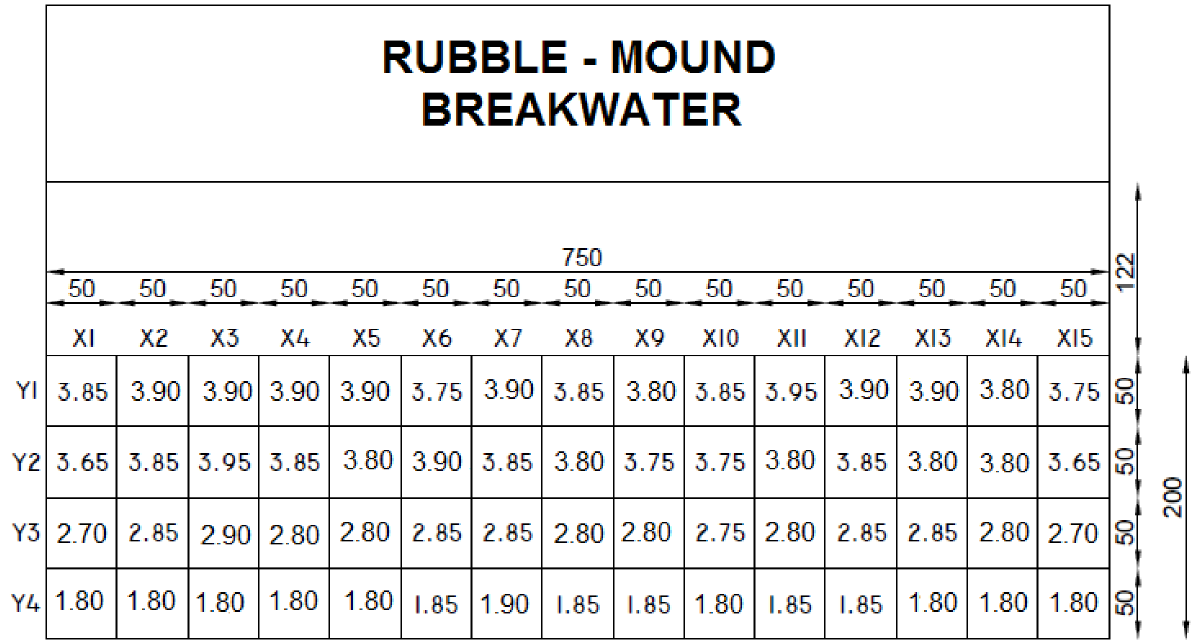


Figure 6. Side view of the sand thickness of the research area

3. Results and discussion

Data of the sediment thickness before and after being loaded with daily or extreme waves simulations were obtained from the experiments in the laboratory. The change in sediment thickness in front of the submerged rubble-mound breakwater were examined. These readings of sediment thicknesses were carried out using nails at 60 observation points in the sedimentation research area.

Based on data obtained from laboratory testing of sediment before and after being loaded with the daily waves, there was a reduction in sediment thickness at 60 points as shown in Figure 7. The change that occured in the sediment thickness are very varied at each observation point with decreasing in sediment thickness by 0.05 cm – 0.35 cm at certain observation points.



	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15
Y1	3.85	3.90	3.90	3.90	3.90	3.75	3.90	3.85	3.80	3.85	3.95	3.90	3.90	3.80	3.75
Y2	3.65	3.85	3.95	3.85	3.80	3.90	3.85	3.80	3.75	3.75	3.80	3.85	3.80	3.80	3.65
Y3	2.70	2.85	2.90	2.80	2.80	2.85	2.85	2.80	2.80	2.75	2.80	2.85	2.85	2.80	2.70
Y4	1.80	1.80	1.80	1.80	1.80	1.85	1.90	1.85	1.85	1.80	1.85	1.85	1.80	1.80	1.80

units: centimeter

Figure 7. Changes in sediment thickness due to daily waves simulation

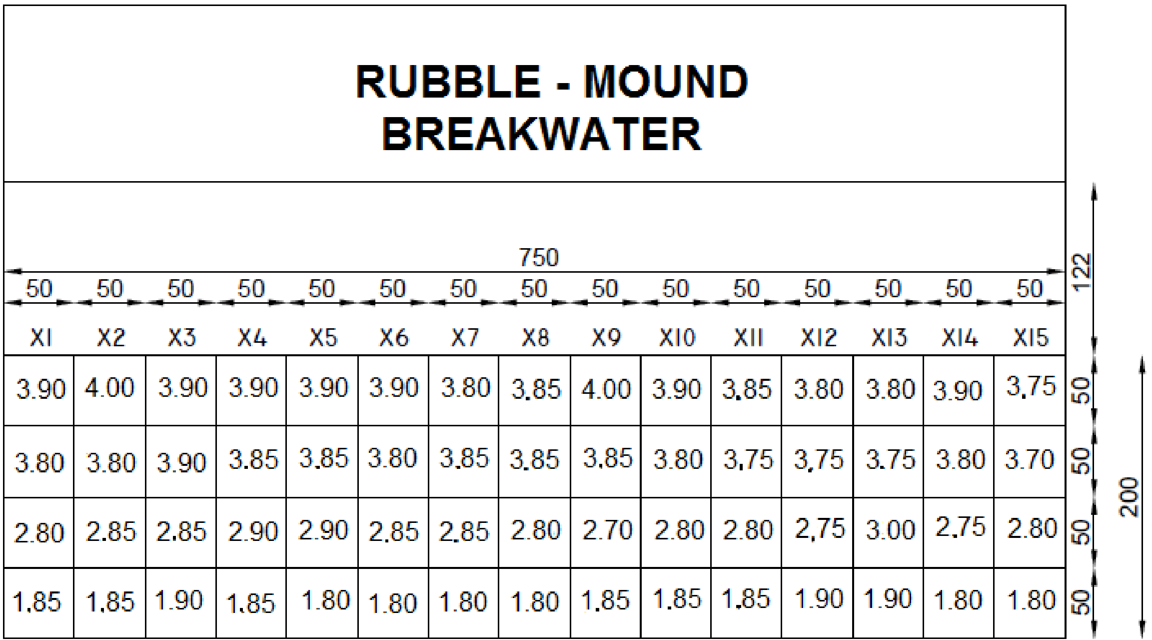
By comparing the sediment thickness changes before and after being loaded with daily waves simulation, the percentage of decreasing in sediment thickness at each observation point was determined as presented in Table 3. Figure 7 dan Table 3 indicate the observation points that experienced a decrease in sediment thickness.

Table 3. Percentage of decrease in sediment thickness at each point due to daily waves simulation

Points	Y1	Y2	Y3	Y4
X1	3.75	8.75	10.00	10.00
X2	2.50	3.75	5.00	10.00
X3	2.50	1.25	3.33	10.00
X4	2.50	3.75	6.67	10.00
X5	2.50	5.00	6.67	10.00
X6	6.25	2.50	5.00	7.50
X7	2.50	3.75	5.00	5.00
X8	3.75	5.00	6.67	7.50
X9	5.00	6.25	6.67	7.50
X10	3.75	6.25	8.33	10.00
X11	1.25	5.00	6.67	7.50
X12	2.50	3.75	5.00	7.50
X13	2.50	5.00	5.00	10.00
X14	5.00	5.00	6.67	10.00
X15	6.25	8.75	10.00	10.00

units: percentage (%)

The analysis of the data obtained was carried out after being loaded with extreme waves simulation in front of the submerged rubble-mound breakwater. It was found that there was a decrease in sediment thickness at 57 sediment review points. Three sediment thickness review points did not change. Changes that occured caused reduction in sediment thickness by 0 – 0.30 cm at certain observation points. Figure 7 displays the changes in sediment thickness in front of the submerged rubble- mound breakwater due to extreme waves simulation.



	XI	X2	X3	X4	X5	X6	X7	X8	X9	XI0	XII	XI2	XI3	XI4	XI5
YI	3.90	4.00	3.90	3.90	3.90	3.90	3.80	3.85	4.00	3.90	3.85	3.80	3.80	3.90	3,75
Y2	3.80	3.80	3.90	3.85	3.85	3.80	3.85	3.85	3.85	3.80	3.75	3,75	3.75	3.80	3.70
Y3	2.80	2.85	2.85	2.90	2.90	2.85	2.85	2.80	2.70	2.80	2.80	2,75	3.00	2,75	2.80
Y4	1,85	1,85	1.90	1.85	1.80	1.80	1.80	1.80	1.85	1.85	1.85	1.90	1.90	1.80	1.80

units: centimeter

Figure 8. Changes in sediment thickness due to extreme waves simulation

The percentage of the decrease in sediment thickness at each point due to extreme wave simulation is presented in Table 4. The results show that both daily and extreme waves simulations decrease the sediment thickness the most at the outer side of the study area facing in the incident waves. The decrease in sediment thickness due to daily waves simulation is higher than due to extreme waves simulation.

Table 4. Percentage of reduce in sediment at each point due to extreme waves simulation

Points	Y1	Y2	Y3	Y4
X1	2.50	5.00	6.67	7.50
X2	0.00	5.00	5.00	7.50
X3	2.50	2.50	5.00	7.50
X4	2.50	3.75	3.33	5.00
X5	2.50	3.75	3.33	7.50
X6	2.50	5.00	5.00	10.00
X7	5.00	3.75	5.00	10.00
X8	3.75	3.75	6.67	10.00
X9	0.00	3.75	10.00	7.50
X10	2.50	5.00	6.67	7.50
X11	3.75	6.25	6.67	7.50
X12	5.00	6.25	8.33	5.00
X13	5.00	6.25	0.00	5.00
X14	2.50	5.00	8.33	10.00
X15	6.25	7.50	6.67	10.00

units: percentage (%)

The data obtained from the laboratory test contain numeric XY sediment research area coordinate and Z values contain the sediment thickness. The irregularly spaced XYZ data interpolate into regularly spaced grid using Surfer software as a grid-based mapping program. The grid from the results of changing in sediment thickness was used to describe the condition of the sediment in front of the submerged rubble-mound breakwater after being loaded by daily and extreme waves simulations. The grid was also used to produce contour and 3D surface that best represents data [19].

The results from the Surfer describe the changing in sediment thickness at each observation point. Figure 9 presents the contour of sediment in front of the submerged rubble-mound breakwater using Surfer after loaded with daily and extreme waves simulations. Based on the contour images shown in Figure 9, the contour of sediment thickness changes at every observation point, where each observation point experiences the decreasing in sediment thickness. The outer sides of the study area facing the incident waves significantly reduce in sediment thickness.

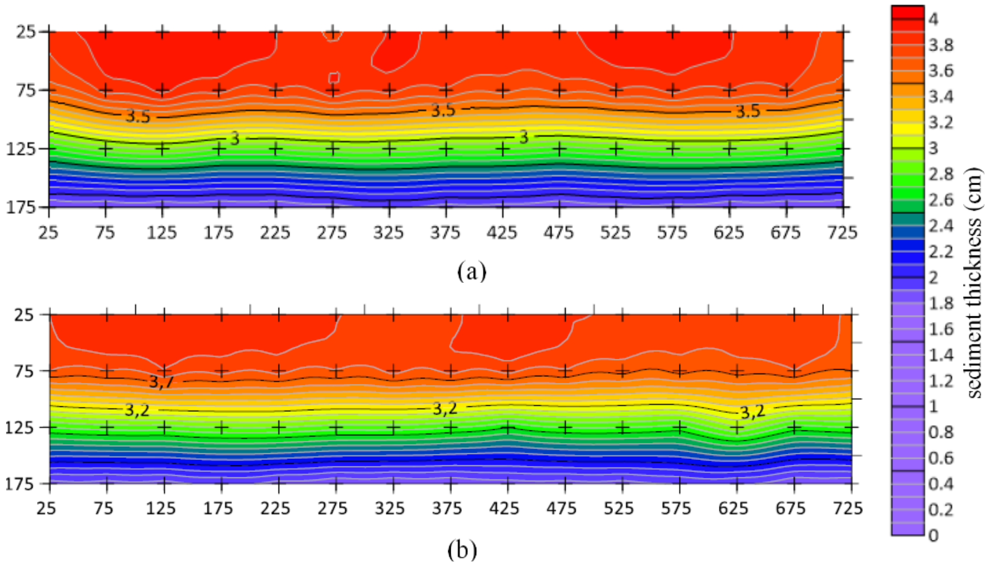


Figure 9. Contour of sediment in front of the submerged rubble-mound breakwater using surfer software after loaded with (a) daily waves simulation and (b) extreme waves simulation

In addition to the contour images, the Surfer also provides an output of 3D images to describe the sediment conditions in the study area. The output 3D images illustrate the condition of the sediment thickness due to daily waves which can be seen in Figure 10. The 3D image of the sediment condition after being loaded with daily waves only illustrates the observation point which according to the data obtained has decreased in sediment thickness. In the outer side of the sediment research area facing the incident wave is 8.8% of reducing in sediment thickness due to daily waves. The output of the Surfer can be compared with the image of the sediment condition after being loaded with daily waves in the laboratory field in Figure 11. It is shown from Figure 10 dan 11 that the scour/deposition pattern in front of the rubble-mound breakwater emerges in the form of alternating scour and deposition areas lying parallel to the submerged rubble-mound breakwater. On the other hand, the outer side of the sediment review area facing the direction of the waves achieves 7.83% of decreasing in sediment thickness due to extreme waves. In the case of the extreme waves simulatiom, the scour depth in front of submerged breakwater decreases with respect to that experienced in the case of the daily waves simulation. This is expected because the streaming in the extreme waves is weaker due to the smaller reflection, therefore, the resulting scour will be smaller than that of the daily waves (varied of the water depth and wave height).

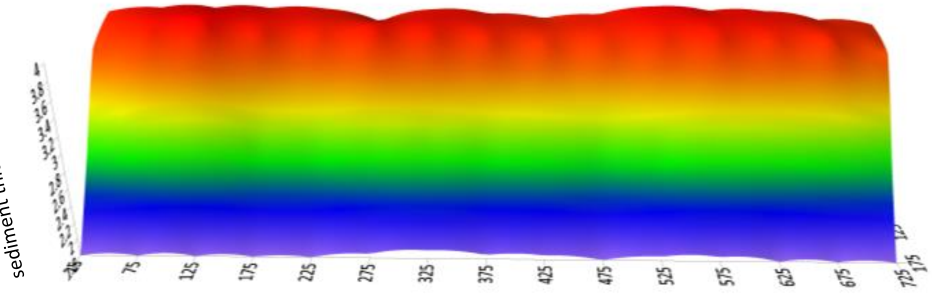


Figure 10. 3D front side of sediment after loading daily waves simulation

Figure 11. Sediment condition after loaded with daily waves simulation

4. Conclusions

Sedimentation in front of the rubble-mound breakwater due to daily and extreme waves simulations was observed with a length of 750 cm and a width of 200 cm. The results of the analysis of all observation points in the sedimentation study area experienced erosion, but the scour that occurred was not constant. The maximum sediment erosion occurred in the outer side of the sediment research area facing the incident waves. Due to daily waves simulation, all the observation points reduced the sediment thickness. On the other hand, three sediment thickness review points did not change, and 57 (fifty-seven) sediment thickness review points were decreased due to extreme waves simulation. The maximum sediment scouring occurs in the outer side of the sediment review area facing the incident waves also obtained by using Suffer software, the scour was 8.8% and 7.83% due to daily and extreme waves, respectively. The scour in front of the submerged rubble-mound breakwater due to daily waves was greater than due to extreme waves because the wave reflection due to extreme waves was weaker than due to daily waves.

Suggestions that can be given based on the results of laboratory tests for sedimentation testing in front of the three-dimensional submerged rubble-mound breakwater which are loaded by daily waves and extreme waves are increasing the number of observation points in the sedimentation research area. By decreasing the distance between the observation points, the data obtained will be more accurate. Thus, not only scour data, but also sediment deposition data in the observation area can be found. Analysis and modelling in future research can be done in more detail. Furthermore, the impact of sedimentation on stability of the submerged rubble-mound breakwater due to daily and extreme waves simulation will be studied in future research.

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