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The Influence of Slopes to the Stability of Stones in front of Seawall

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ABSTRACT

Seawall is a coastal protection structure to prevent coastal erosion from wave forces. In this research, rubble-mound of stones are used as armor due to the availability of the material in coastal areas and ease of construction. A series of physical model tests with a scale of 1:25 with a variation of four wave heights (H), two wave periods (T), and three different slopes of rubble-mound in front of seawall were performed. Parameters used in the research are stability coefficient (K_D),wave steepness (H/gT^2), and percentage of damages (Do). The slope variations of rubble-mound were 1:1.15, 1:1.5, and 1:2. The experiments also displayed that the stone stability coefficient (K_D) directly proportional with wave steepness (H/gT^2). The value of K_D for the seawall model with the slope angle of cot = 1.15 is 4.4, cot = 1.5 is 4.28 and cot = 2 is 3.02. From all three variations of slope, the most stable is on the slope 1:2 with the least damage impact on the model. The gentlest slope is the most stable structure.

Keywords: *seawall, rubble-mound, physical model, stability coefficient.*

1. INTRODUCTION

The coast is defined as the area at the edge of a body of water located both above and beneath the waterline from the highest tide. The coastal region is currently used for ports, residential, and industrial areas. Various tourist attractions are also commonly found in coastal zone. This condition highly increases the demand for coastal areas and the infrastructure needed to support them. Such activities may create problems such as erosion, sedimentation, environmental disturbance to water quality and coral reefs. The coastal erosion being the most common problem and causes the shoreline to retreat. Abrasion is also an issue which reduces the rocky coastal area and damages structures [1]. Natural factors such as ocean currents and waves also affect the coastal area. A coastal area requires shelter from wave forces with coastal protection structures such as breakwaters, seawalls, revetments, groins, and jetties.

A seawall is a structure that separates the land and water area to protect coast and shoreline from erosion and wave overtopping. A seawall is built to strengthen the shoreline to prevent erosion taking place due to incoming wave forces [2]. Seawall run parallel to the beach and can be built of concrete, wood, steel, or boulders. Seawall were also called as bulkheads or revetments, the distinction is mainly a matter of purpose [3]. Seawall is a structure that not only provides shoreline protection from waves but also retains soil. Bulkhead is a vertical shoreline stabilization structure that primarily retains soil and provides minimal protection from waves. Seawall are typically located on the coast fronting beaches, and are subject to storm surges with pounding surf, eroding shorelines and wave overtopping from coastal storm events [4].

Most of coastal protection structure failures were due to imperfect design or construction or not complying with the required technical design. The shape of an armor unit has a key role because of it will affect the stability coefficient (K_D = Coefficient of Hydraulic Stability) of the unit [5].

In this study a stone rubble-mound was selected as toe protection of the seawall. It is chosen, as the material are relatively cheap, abundant availability, and the ease of construction. A rubble-mound seawall is expected to have enough stability to withstand waves that hit it. The model of seawall will be built to investigate the stability of the armor stones. The slope of the rubble-mound was varied. The expected output from this study are the stability coefficient of armor stones rubble-mound as seawall toe protection.

2. MATERIAL AND METHODS

In this study, several stages of preparation for the testing of the model were presented as follows.

2.1 Preparation of Material Testing

The upright part of seawall model was constructed with wooden beams with a length of 0.5 meters, 0.3 meters width, with a height of 1 meter and covered with a layer of plywood on each side. The model was built based on 1:25 Froude's scale. The rubble-mound was created in conventional 3 layers. The inner layer made of stacks of sandbags covering with gravel as the intermediate layer, and finally the outer layer was a 2-layers stone. The water depth of the model was 0.5 meter as shown in Figure 1.

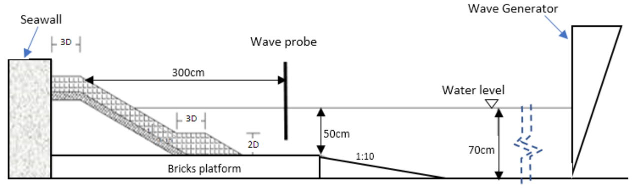

Figure 1. Sketch of test in the wave tank – side view

The test was performed with variations of wave height, wave period, and slopes. The wave height inputs were 0.03 meter. 0.05 meter, 0.06 meter, and 0.07 meter. The wave period for all tests was set 1.2 seconds except the smallest wave height (0.03m) also tested for 1.4 second.

Table 1. Testing Variations

Slope	Wave Height [m]	Wave Period [second]
1:1.15	0.03	1.2
		1.4
	0.05	1.2
	0.06	
	0.07	
1:1.5	0.03	1.2
		1.4
	0.05	1.2
	0.06	
	0.07	
1:2	0.03	1.2
		1.4
	0.05	1.2
	0.06	
	0.07	

The armor material for the rubble-mound in front of seawall were composed of stones. In this test, typical rubble stone with diameter of 0.07 meter, density of 1450 kg/m^3, and weight about 0.3 kg were used. For the convenience of observation and counting stone displacements, the 2 layers outer armor stones were colored and divided into 6 zones based on their colors. The zones consisted of upper red zone, upper green zone, upper yellow zone, lower red zone, lower green zone, and lower yellow zone. The wave run-up occurred on the upper green zone, whereas the wave run-down occurred on the upper yellow zone as shown in Figure 2 below.

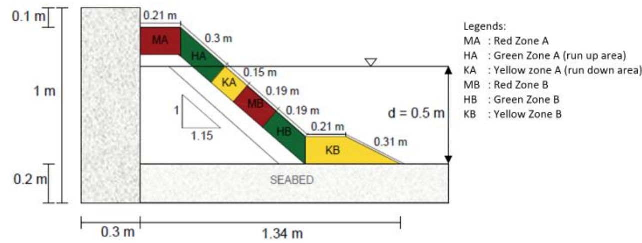

Figure 2. Sketch of color zones for the slope angle of 1:1.15

The model was scaled based on Froude's number, i.e: a ratio between inertia force and gravitational acceleration. If inertial force (mass times acceleration) is expressed in the form of $F_I = \rho.L^2.U^2$ and gravity force (mass times gravitational acceleration) is expressed as $F_W = \rho L^3.g$, the equation of Froude's number is:

$$Fr = \frac{F_I}{F_W} = \frac{\rho U^2 L^2}{\rho g L^3} = \frac{U^2}{gL} \qquad (1)$$

where ρ is the density [kg/m^3], L is the specific length [m], U is the specific velocity [m/s], and g is gravitational acceleration [m/s^2] [6].

The experiment was performed without distortion, this implies that the scale in vertical direction and scale in horizontal direction are the same. Then the scale of length (nL), time (nT) and weight (nW) are expressed as:

$$nL = nH = nd \qquad (2)$$

$$nT = \sqrt{n_L} \qquad (3)$$

$$nW = nL^3 \qquad (4)$$

where, H is the wave height, d is the water depth, T is wave period, W is armour unit weight.

To reduce the scale effects due to the lack of similarity of viscous forces, the experiments is set such as such that Reynolds number (Rn) is above 3 x 10^4 [7],[8] and expressed as [6]:

$$Rn = \frac{L\sqrt{gH}}{\nu} \qquad (5)$$

where υ is water kinematic viscosity (at 30^o C ≈ 8.10^{-7} m/s^2). Table 2 lists the typical size of the variables:

Table 2. Variable of Model Scale

No	Parameters (notation) – [unit]	Prototype	Model	Scale
1	Specific length (L) – [m]	1.75	0.07	1:25
2	Water depth (d) – [m]	12.5	0.5	1:25
3	Wave height (H) – [m]	1.75	0.07	1:25
4	Wave period (T) – [s]	7	1.4	$1:\sqrt{25}$
5	Typical Weight (W) – [kg]	4687.5	0.3	1:25^3

2.2 Testing and Visual Observation

The physical model test was performed in a wave flume tank in the Energy and Marine Environment Laboratory of the Ocean Engineering Department Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember, Surabaya. As shown in Figure 1 above, a wave probe was placed 3 meters in front of the model to record the water fluctuation. Total of 15 test variations were executed, and each test generated 3000 waves for over 50 minutes. A pause of 10 minutes between each test were taken to evaluate the movement of the stones, reshaping the slope as well as returning water level to its tranquil initial states.

The condition of the test model before and after the test were photographed and compared. A video was taken for the duration of the test to record critical events such as the displacement of stones. The amount and weight of the displaced stones were recorded.

3. RESULT AND DISCUSSIONS

3.1 Wave Data

To determine the significant wave height (Hs) and peak wave period (Tp), the water fluctuations records were analyzed using AnaWare [9] as shown in Figure 3 below:

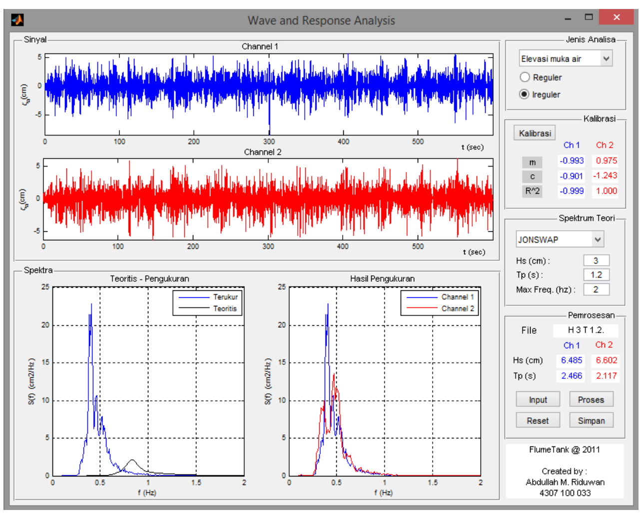

Figure 3. AnaWare Graphical User Interface [9]

Wave variables used in this study obtained from analysis of recorded wave of Channel 1 in Figure 3, which are the readings of the wave probe located 3 meters in front of the test model. Chanel 2 was the probe located close to wave generator, and do not considered in this study.

Most of the initial value for wave generator input for wave height (H_{inp}) and period (T_{inp}) resulting higher value of recorded wave variables from wave probe. The recorded significant wave height (Hs) mostly twice of inputted wave height (H_{inp}), while the peak wave period is about 20%—30% higher than inputted wave periods (T_{inp}) as listed in Table 3 below:

Table 3. Wave Height and Wave Period Readings

Test No.	Slope	H_{inp}	Hs	T_{inp}	Tp
		cm		second	
1	1:1.15	3	6.178	1.2	1.602
2		3	6.094	1.4	1.645
3		5	10.785	1.2	1.529
4		6	13.167	1.2	1.592
5		7	14.095	1.2	1.586
6	1:1.5	3	6.688	1.2	1.677
7		3	6.599	1.4	1.718
8		5	11.975	1.2	1.607
9		6	13.818	1.2	1.656
10		7	14.562	1.2	1.629
11	1:2	3	7.217	1.2	1.628
12		3	6.463	1.4	1.717
13		5	11.574	1.2	1.611
14		6	13.342	1.2	1.650
15		7	14.198	1.2	1.613

The discrepancy of input and output of generated waves due to disturbance on transfer signal process from wave generator software to the hardware. However, as this disturbance is consistent, the recorded wave from probes were considered in the analysis in this study.

3.2 Visual Observations of the Test

Visual observation was carried out throughout the duration of the test by video recording and taking photographs. The stability of stones evaluated based on the displacement of individual stones from their zones. As the stones were colored, it is clearly seen that stones with different color coming from which neighborhood zones. It can also be evaluated whether run up or run down process displaced the stones. The displaced stones from their zone were counted and marked as unstable in the observation sheet. Figure 4 below shows typical results of the experiment, before and after wave attacks.

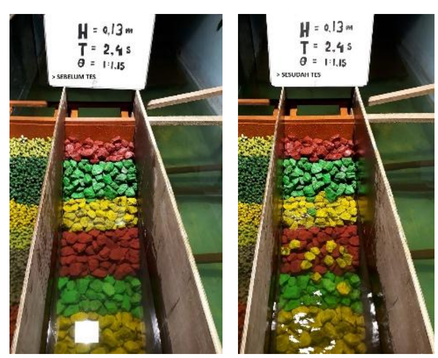

Figure 4. Condition of the model before and after wave attack

Table 4 below shows the visual observation results of all 3 models with the slope angle of 1:1.15, 1:1.5, and 1:2.

Table 4. Visual Observation Results of Test Model

Test No.	Slope	Hs cm	Tp second	Status
1	1:1.15	6.1780	1.6024	STABLE
2		6.0939	1.6448	STABLE
3		10.7849	1.5292	UNSTABLE
4		13.1666	1.5921	UNSTABLE
5		14.0945	1.5856	UNSTABLE
6	1:1.5	6.6881	1.6767	STABLE
7		6.5991	1.7180	STABLE
8		11.9745	1.6069	UNSTABLE
9		13.8180	1.6559	UNSTABLE
10		14.5623	1.6285	UNSTABLE
11	1:2	7.2174	1.6277	STABLE
12		6.4632	1.7168	STABLE
13		11.5744	1.6108	STABLE
14		13.3424	1.6503	UNSTABLE
15		14.1976	1.6129	UNSTABLE

The “STABLE” status indicates no movement of the stones after the test. Meanwhile, the “UNSTABLE” status shows a minimal movement of one stone after the test model. The percentage of damage was calculated based on the definition in the 1984 Shore Protection Manual; a ratio of the number of displaced stones over the number of stones within active zones. [10] The exact amount of displaced stones that were observed as UNSTABLE in Table 4 above were counted and presented in Table 5:

Table 5. Summary of Displaced Stones from each Test

Slope	Hs cm	Tp second	Number of Displaced Stones (Per zone)		
			Run Up	Run Down	Amount
1:1.15	6.178	1.602	0	0	0
	6.093	1.644	0	0	0
	10.784	1.529	0	3	3
	13.166	1.592	1	6	7
	14.094	1.585	1	13	14
1:1.5	6.688	1.676	0	0	0
	6.599	1.71	0	0	0
	11.974	1.606	0	1	1
	13.81	1.655	0	1	1
	14.562	1.628	1	4	5
1:2	7.217	1.627	0	0	0
	6.463	1.716	0	0	0
	11.574	1.610	0	0	0
	13.342	1.650	0	1	1
	14.197	1.612	0	3	3
		Amount	3	32	35

The displacement of stones occurred only in the run up and run-down zones. It is observed that more stones were displaced from the wave run down zone, moved up to run up zones. At the slope angle of 1:1.15, a total of 24 stones were displaced, in which 2 were displaced from the wave run up zone and 22 were displaced from the wave run down zone. For a slope angle of 1:1.5, a total of 7 stones were displaced, with 1 stone displaced from the wave run up zone and 6 were displaced from the wave run down zone. At the 1:2 slope angle, a total of 4 stones were displaced and all were in the wave run down zone. The rest of the zones had no displacements. As seen in Table 5 above, highest wave attacked at steepest slope resulted more displaced stones than others.

3.3 Effect of Wave Height (H) on Damage Percent (Do)

Figure 5 shows the influences of wave height (H) to the damage (Do). It is shown that the wave height is directly proportional with damage. A higher wave height will have a bigger damage on the model, while a smaller wave height will have less damage on the model.

A steeper slope of the stones will also result in a higher amount of displaced stones, indicating that the model is unstable. A gentle slope results in a more stable model, proven by a lesser amount of displaced stones. Figure 5 below shows the influences of wave height to the damage of armour stones.

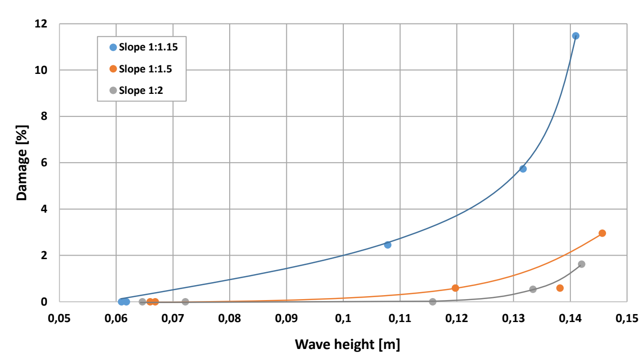

Figure 5. Influences of wave height (H) to damage (Do)

3.4 Effect of Wave Steepness (H/gT^2) on the Stability Coefficient (K_D)

The relationship between wave steepness (H/gT^2) and the stability coefficient (K_D) based on Hudson's formula [11] shows that the increment of wave steepness is directly proportional with the increment of the stability coefficient.

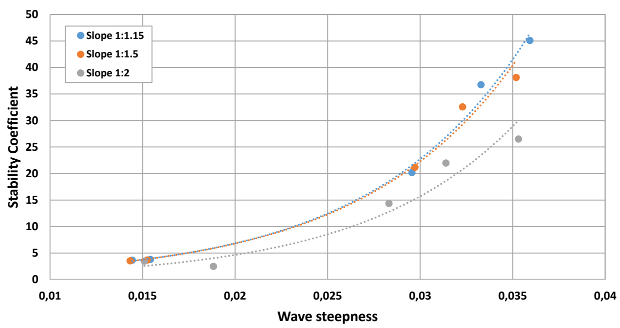

Figure 6. Influences of wave steepness (H/gT^2) to stability coefficient (K_D)

The wave steepness is a ratio of the wave height (H) to the wavelength (gT^2) or wave period (T). Highest wave steepness also means the increment of the wave height. Meanwhile, the wave steepness is inversely proportional with the wave period, where a higher wave steepness also product of a lower wave period. A higher wave steepness will eventually break the waves and creates instability of armor stones.

Table 6. Calculation of significant wave height (Hs) and coefficient of stability (K_D)

Slopes	Hs meter	Tp second	H/gT^2	K_D	Damage %
1:1.15	0.0618	1.6024	0.0154	3.7986	0
	0.0609	1.6448	0.0144	3.6456	0
	0.1078	1.5292	0.0296	20.2082	2.4590
	0.1317	1.5921	0.0333	36.7706	5.7377
	0.1409	1.5856	0.0359	45.1054	11.4754
1:1.5	0.0754	1.6767	0.0172	5.2891	0
	0.0660	1.7180	0.0143	3.5493	0
	0.1197	1.6069	0.0297	21.2060	0.5917
	0.1382	1.6559	0.0323	32.5853	0.5917
	0.1456	1.6285	0.0352	38.1396	2.9586
1:2	0.0722	1.6277	0.0151	3.4825	0
	0.0646	1.7168	0.0188	2.5009	0
	0.1157	1.6108	0.0283	14.3629	0
	0.1334	1.6503	0.0314	22.0013	0.5405
	0.1420	1.6129	0.0353	26.5089	1.6216

3.5 Comparison with another Research

In general, the relation between wave height (H) and damage percent (Do) tends to increase which is similar to previous research . The wave height is directly proportional with the damage done to the structure, with a higher wave height dealing more damage and a smaller wave height dealing less damage to the structure.

For example, a research at USACE is compared to this study as shown in Figure 7. The scatter diagram below shows the influences of wave height to the damage of the armor stones between this study with the results from the research by Carver and Dubose at USACE [12].

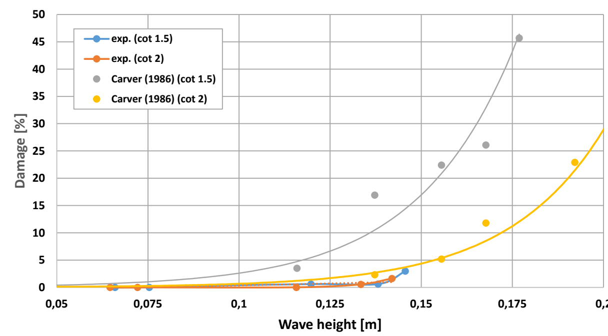

Figure 7. Scatter diagram comparison with another research

From the figure above, the percentage of damage observed in this research has a smaller value than the results from Carver and Dubose [12]. This is due to the differences in the geometry of the structure, average weight of the armor stones, and the variation of waves in the test. These factors affected the amount of stones that were displaced. The average weight of stones used in this test were about 350 grams, while the average weight of stones used in the tests performed by Carver were about 250 grams. Heavier stones were stable compared to the light ones. Furthermore, the variation of wave height used in the tests performed by Carver and Dubose [12] are greater as listed in the following table:

Table 7. Comparison of wave height (H) and percentage of damage (Do)

Model	Range of Value H (m)	Range of Value Do (%)
cot 1.15	0.0660-0.1456	0 - 2.9
cot 2	0.0646-0.1420	0 - 1.6
cot 1.15 [12]	0.1159-0.1769	3.5 - 45.7
cot 2 [12]	0.1373-0.2013	2.3 - 24.8

The range of wave height are at Carver and Dubose [12] experiments were between 14-20 cm. The range of weight height used in this study were between 6-14 cm. The range of wave period used in the tests performed by Carver and

Dubose were between 1.18-2.82 seconds, while this study use wave period between 1.59 - 1.72 seconds. The wave steepness of Carver and Dubose were higher than those in this study. Furthermore, armor stability is influenced by wave period with the lower stabilities being observed at the longer wave periods in shallower water [13].

4. CONCLUSION

Based on tests and results described in this study, which the stone armor stability was evaluated for toe protection of the sea wall, the following conclusions can be achieved:

1) A rubble mound with steeper slope will result in a higher damage percent (Do), as shown by the higher amount of displaced stones. The damage at the slope of 1:1.15 with significant wave height (Hs) of 0.14 m was the highest percentage of damage of 11.4754 %. At a slope of 1:1.5 the higher percentage of damage was 2.9586% and at a slope 1:1.2 the highest percentage of damage was 1.6216% for the same significant wave height.
2) Higher wave steepness will eventually break the waves and creates instability of armor stones. This results in smaller wave forces experienced by the rubble mound seawall and increasing the K_D. A higher wave steepness will result in a higher stability coefficient (K_D). The stability coefficient at a slope 1: 1.15 was 3.7986, a slope 1: 1.5 was 3.6948, and a slope 1: 2 was 3.4825.
3) Visual observations taken throughout the test, shows that the stones highly displaced at the run up and run down zones. The stones at run down zone was more prone to displacement than run up zones. At the slope of 1:1.15, a total of 24 stones were displaced, in which 2 were displaced from the wave run up zone and 22 were displaced from the wave run down zone. For a slope of 1:1.5, a total of 7 stones were displaced, with 1 stone displaced from the wave run up zone and 6 were displaced from the wave run down zone. At the 1:2 slope, a total of 4 stones were displaced and all were in the wave run down zones.

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