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Article

Physical model analysis of stability coefficient for tetrapod innovation

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Abstract: Beach protection is vital to reduce the damage to shorelines and coastal areas; one of the artificial protections that can be utilized is the tetrapod. However, much damage occurred when using a traditional tetrapod due to the lack of stability coefficient (K_D). Therefore, this research aims to increase the stability coefficient by providing minor modifications to the cape of the tetrapod, such as round-caped or cube-caped. The modification seeks to hold the drag force from the wave and offer a good interlocking in between the tetrapod. This research applied physical model test research using a breakwater model made from the proposed innovative tetrapod with numerous variations in dimensions and layers simulated with several scenarios. The analysis was carried out by graphing the relationship between the parameters of the measurement results and the relationship between dimensionless parameters, such as wave steepness H/gT2, and other essential parameters, such as the K_D stability number and the level of damage in %. The result shows that the modified and innovative tetrapod has a more excellent K_D value than the conventional tetrapod. In addition, the innovative tetrapod with the cube-shaped has a recommended K_D value greater than the round shape. This means that for the modified tetrapod structure and the same level of security, the required weight of the tetrapod with the cube cap will be lighter than the tetrapod with the round cap. These findings have significant practical implications for coastal protection and engineering, potentially leading to more efficient and cost-effective solutions.

Keywords: innovative tetrapod; stability coefficient; physical model; round; cube

1. Introduction

Coastal areas have rich potential in natural resources such as fisheries, mangroves, coral reefs, etc. Coastal areas are usually used for tourism, ports, trade, and agriculture (Gong et al., 2023; Mejjad et al., 2022; Miah et al., 2023; Singh, 2020). In Bali, the coastal area is also used for traditional events. Thus, the coastal areas in Bali have a high economic value which must be preserved (Lukman, 2020; Suteja et al., 2021). Coastal areas can experience damage from human intervention and natural influences, such as erosion, abrasion, accretion, and beach pollution (Amalia and Nur, 2023; Asmal et al., 2024; Dutra et al., 2021; Hait and Sahu, 2024; Lincoln et al., 2023; Paul et al., 2022; Solihuddin et al., 2021; Suyarso et al., 2023; Van Nam and Hung, 2022). Beaches already have natural protection, such as sand, coral, and mangroves. Still, if natural beach protection can no longer protect the beach, artificial protection can be used.

Artificial protection can be in coastal buildings, such as breakwaters, groins, jetties, seawalls, or revetments. Coastal protection materials can be natural stone or concrete (Perricone et al., 2023). Due to the limited availability of natural stone, many artificial stones made from concrete have been developed, including tetrapod, quadruped, hexapod, dolos, polypod, and others. Research on polypods was carried out by conducting physical model simulations in the laboratory (Arifandi and Suharjoko, 2021). Meanwhile, research on tetrapod has been carried out for a long time and has been widely used in several countries to protect their beaches. Pierre Danel and Paul Anglès d'Auriac from the Laboratoire Dauphinois d'Hydraulique in Grenoble, France developed the tetrapod in 1950 (Natakusumah et al., 2024). Subsequently, the tetrapod was widely used along the coast of Japan. Tetrapod is also commonly used in Indonesia to protect beaches experiencing erosion or abrasion (Akyol, 2022; Nyoman and Dayanti, 2021; Zafaruddin and Masirin, 2022).

Another research has done testing of the tetrapod model in the laboratory and proposed a formula (Suh and Kang, 2012). The proposed formula is proven to be applicable to breakwaters with various inclination angles. Testing of the load-bearing capacity of tetrapod where reinforced concrete was added with Fiber-Synthetic-Polymer and proved that the application of the calculation procedures used was suitable for evaluating the load-bearing capacity of concrete tetrapod (Unuk and Kuhta, 2022). Several factors have been analyzed that influence the failure of coastal protective buildings, one of which is the throwing of concrete from coastal building structures (Çelikoğlu and Engin, 2017). High waves and the lack of binding force between the concrete cause this. In this research, the conventional tetrapod shape was developed to increase its binding capacity by increasing its stability rate.

Tetrapod has been used in many projects as armor, according to the advice of some experts. However, much damage occurred by using traditional tetrapod due to the lack of the stability coefficient (K_D) (United States. Army. Corps of Engineers, 1984), where the K_D value of Tetrapod is only around 7 to 8. Therefore, there are a lot of armor types that can increase the stability coefficient, such as dolos (Jensen et al., 2024; Molines et al., 2021; Olivier, 2022; Perricone et al., 2023; Wurjanto and Hardaya, 2022). However, the tetrapod configuration with four legs could offer more stability than the others. In this research, minor modifications to the cape of the tetrapod, such as round-caped or cube-caped, will increase the stability coefficient hypothetically. This is because this modification will hold the drag force from the wave and offer good interlocking between the tetrapods. This new model and innovative tetrapod should be tested to validate this assumption. Model experimentation is one of the best methods to find the stability coefficient number.

2. Materials and method

2.1. Current tetrapod design

Pierre Danel and Paul Anglès d'Auriac initially developed tetrapods in Grenoble, France, in 1950 (Natakusumah et al., 2024). Since then, tetrapods have been widely used worldwide as the armor of breakwater structures. The stability coefficient (K_D) is one parameter that determines a tetrapod's structural stability. **Table 1** shows the values of K_D for various armor units. For tetrapods, K_D ranges from 3.5 to 8.

Table 1. Values of stability coefficient (United States. Army. Corps of Engineers, 1984; US Army Corps of Engineers, 1992).

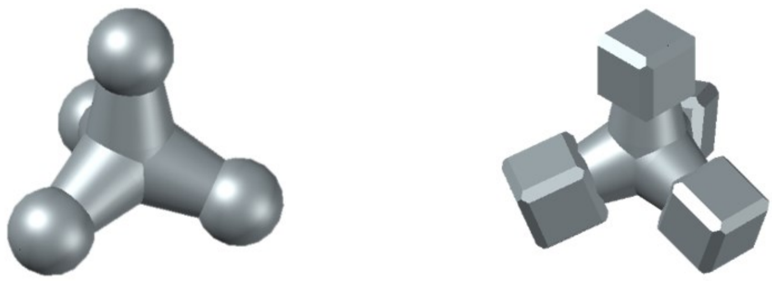
No damage criteria and minor overtopping							
			Structure Trunk		**Structure Head**		
Armor Units	N[c]	Placement	K_D[b]		K_D		Slope
			Breaking	Nonbreaking	Breaking	Nonbreaking	Cotθ
Quarrystone	2	Random	1.2	2.4	1.1	1.9	1.5–3.0
Smoothrounded	>3	Random	1.6	3.2	1.4	2.3	[e]
Rough angular	1	Random[d]	[d]	2.9	[d]	2.3	[e]
Rough angular	2	Random	2.0	4.0	1.9	3.2	1.5
					1.6	2.8	2.0
					1.3	2.3	3.0
Rough angular	>3	Random	2.2	4.5	2.1	4.2	[e]
Rough angular	2	Special[f]	5.8	7.0	5.3	6.4	[e]
Parallelepiped[g]	2	Special[a]	7.0–20	8.5–24	-	-	-
Tetrapod and Quadripod	2	Random	7	8	5	6	1.5
					4.5	5.5	2
					3.5	4	3
Tribar	2	Random	9	10	8.3	9	1.5
					7.8	8.5	2
					6	6.5	3
Dolos	2	Random	15.8[h]	31.8[h]	8	16	2
					7	14	3[i]
Modified cube	2	Random	6.5	7.5	-	5	[e]
Hexapode	2	Random	8	9.5	5	7	[e]
Toskane	2	Random	11	22	-	-	[e]
Tribar	1	Uniform	12	15	7.5	9.5	[e]
Quarrystone (K_{RR})							
Graded angular	-	Random	22	2.5	-	-	-

[a] CAUTION: Those KD values shown in italics are unsupported by test results and are only provided for preliminary design purposes.
[b] Applicable to slopes ranging from 1 on 1.5 to 1 on 5.
[c] n is the number of units comprising the thickness of the armor layer.
[d] The use of single layer of quarrystone armor units is not recommended for structures subject to breaking waves, and only under special conditions for structures subject to nonbreaking waves. When it is used, the stone should be carefully placed.
[e] Until more information is available on the variation of KD value with slope, the use of KD should be limited to slopes ranging from 1 on 1.5 to 1 on 3. Some armor units tested on a structure head indicate a KD-slope dependence.
[f] Special placement with long axis of stone placed perpendicular to the structure's face.
[g] parallelepiped-shaped stone: long slab-like stone with the long dimension about 3 times the shortest dimension (Markle and Davidson, 1979).
[h] Refers to no-damage criteria (<5 percent displacement, rocking, etc.); if no rocking (<2 percent) is desired, reduce KD 50 percent (Zwamborn and Van Niekerk, 1982).
[i] Stability of dolos on slopes steeper than 1 on 2 should be substantiated by site-specific model tests.

2.2. Innovative tetrapod modification design

Based on the weaknesses of conventional tetrapods, specifically their structural failure and stability coefficient, this research proposes innovation in tetrapod design.

Two types of the proposed design are round-capped tetrapods and cube-capped tetrapods. **Figure 1** shows a tetrapod with a cape design modification that will hypothetically increase the stability coefficient.



(a) **(b)**

Figure 1. Innovative tetrapod cape modification proposed **(a)** round-caped; **(b)** cube-caped.

In this research, geometry scaling is carried out by comparing the prototype and the model, which is taken to be 25. Firstly, the length scale must be determined. Armor mass is calculated using the Equation (1).

$$Nl = \frac{Lp}{Lm} = \frac{1.25}{0.5} = 25 \tag{1}$$

Armor mass is calculated using the Equation (2).

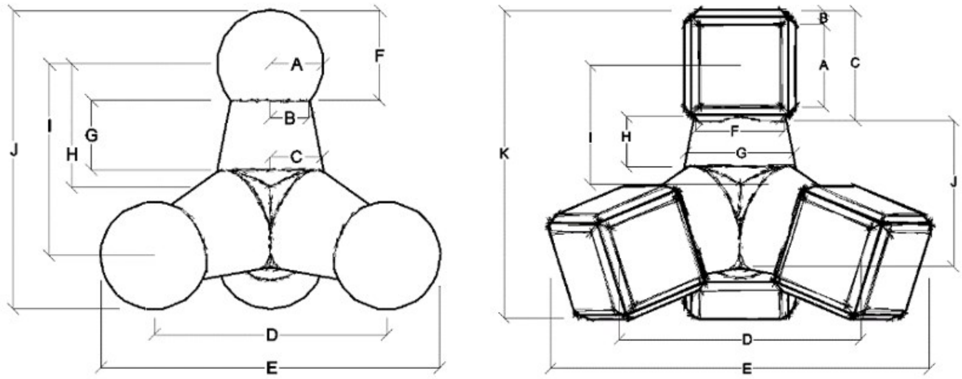
$$\frac{\text{Prototype mass}}{\text{Model mass}} = \left(\frac{Lp}{Lm}\right)^3 \tag{2}$$

The tetrapod model used in this research is concrete, with a scale arranged on a laboratory scale and predetermined model variations. The Froude number of the prototype is arranged to be equal to the model by using the Equation (3).

$$F_r = \frac{v}{\sqrt{gl}} \tag{3}$$

where F_r = Froude Number; v = flow velocity; g = gravitational acceleration; and L = length dimension. Thus, the scale used in modeling is 1: 25. From the Froude number, scaling for other parameters can be derived with Length (L), Wave Height (H), Wave Period (T), and Weight (W).

Thus, a prototype mass was made on the test object of 5 tons and 7 tons for a round-capped and cube-capped tetrapod, as shown in **Figure 1**. The tetrapod was molded using acrylic and made into concrete with a 2400 kg/m^3 density. The weight is adjusted to the 5-ton scenario, 320 grams, and 7 tons, 448 grams. The dimension details of these proposed designs in 2D are shown in **Figure 2**. The innovative tetrapod dimensions prototype and model with a scale of 1:25 are detailed in **Tables 2** and **3**.



(a) (b)

Figure 2. Dimensions of innovative tetrapod **(a)** round-caped; **(b)** cube-caped.

Table 2. Innovative tetrapod round-caped prototype and model dimensions with scale 1:25.

Code	Prototype	Model	Prototype	Model	Unit
Mass	5000	0.320	7000	0.448	kg
A	403.478	16.139	451.461	18.058	mm
B	293.136	11.725	327.926	13.117	mm
C	399.107	15.964	446.475	17.859	mm
D	1767.473	70.699	1977.246	79.090	mm
E	2575.417	103.017	2880.823	115.233	mm
F	681.533	27.261	762.473	30.499	mm
G	528.969	21.159	592.742	23.710	mm
H	936.800	37.472	1049.880	41.995	mm
I	1457.355	58.294	1630.321	65.213	mm
J	2265.503	90.620	2534.266	101.371	mm

Table 3. Innovative tetrapod cube-caped prototype and model dimensions with scale 1:25.

Code	Prototype	Model	Prototype	Model	Unit
Mass	5000	0.320	7000	0.448	kg
A	637	25.480	713	28.520	mm
B	106	4.240	119	4.760	mm
C	849	33.960	950	38.000	mm
D	1881	75.240	2104	84.160	mm
E	2953	118.120	3304	132.160	mm
F	695	27.800	772	30.880	mm
G	849	33.960	950	38.000	mm
H	386	15.440	432	17.280	mm
I	921	36.840	1031	41.240	mm
J	1129	45.160	1263	50.520	mm

2.3. Laboratories equipment

Physical model test research using a breakwater model made from the proposed innovative tetrapod with numerous variations in dimensions and layers simulated with several scenarios at the Coastal Laboratory, Bandung Institute of Technology (ITB Bandung), Bandung City, West Java, Indonesia. The equipment used in this research is a Wave Flume Glass Channel for testing two-dimensional physical models. The glass channel has dimensions of 40 × 1.4 × 1.2 meters with a maximum wave height of 0.45 meters. Other equipment, such as a wave generator and wave gauges, are used to create a regular wave generator and measure changes in water level in physical models. All these equipment are manufactured by HR Wallingford, Oxfordshire, United Kingdom. We used the HR Merlin 2.24 version for running wave maker and Data AcQuisition software (HR DAQ) for data recording.

Several pieces of equipment are needed to evaluate the testing result in the laboratory, such as Data Analysis and Acquisition software to process wave, speed, and pressure data from physical model tests. Next is an electromagnetic water level sensor, which helps measure the height of the water level in physical models. A Three-axis velocity sensor is also used to measure speed in physical models. Another essential piece of equipment is a high-speed camera. To capture the laboratory testing (running).

This research uses clean water within the flume that does not contain mud, oil, or dirt that can damage cleanliness. The innovative tetrapod model used in this research is made of concrete with a scale arranged on a laboratory scale with predetermined model variations. Modeling is carried out using a geometric scale, or geometric unity can be achieved if the ratio of all linear dimensions of the model and prototype is the same. This means that the comparison of all length measurements between the model and the prototype must be comparable. Based on the calibration results in the ITB marine engineering lab, it was found that the maximum height that could be generated was 20 cm, or with a scale of 1:25, the wave height was 5 m.

2.4. Physical model test procedure and flume setup

The setup of the laboratory experiment is shown in **Figure 3**. Tetrapods were put as armor layers, with the core layer filled with sand and aggregate. The breakwater in this experiment follows the rubble-mound model, where the water cannot infiltrate the structure. The innovative tetrapods were colored white, red, blue, and green and were arranged in stages. The wave flume configuration is shown in **Figure 4**. There are four wave gauge instruments in the wave flume, which are located 1 m from the wave generator (WG1), before the changing elevation (WG2), in front of the breakwater (WG3), and behind the breakwater (WG4).

Figure 3. Wave flume setup in the laboratory.

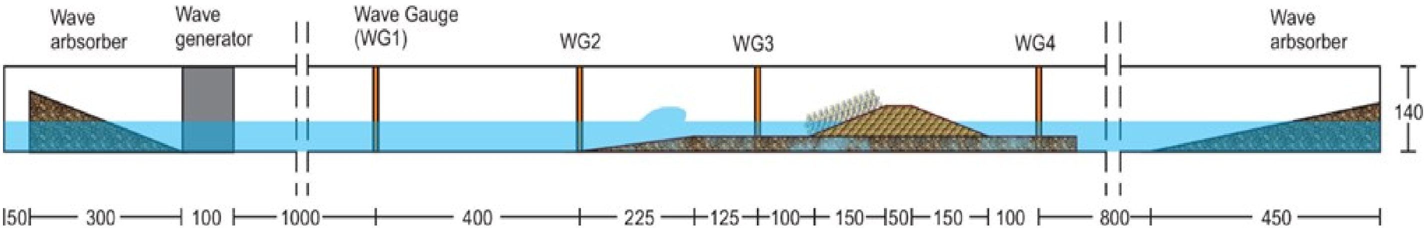


Figure 4. Wave flume setup configuration.

2.5. Experiment procedure and scenario

Several stages of research preparation must be carried out to analyze the stability coefficient of the enhanced tetrapod protective layer unit (innovative tetrapod) on the seawall. These stages are shown in the research flow diagram, **Figure 5**.

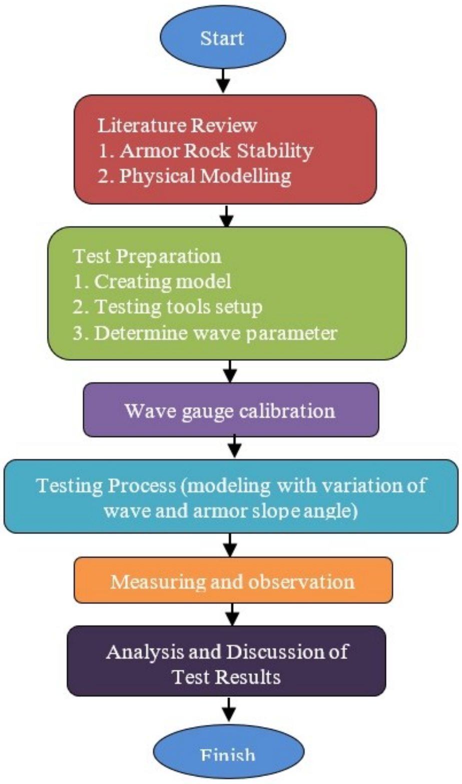


Figure 5. Flowchart diagram.

The experiment scenario can be followed in **Table 4**.

Table 4. Experiment scenario.

Parameters	Detail of Parameters
Slope	1:3 and 1:2
Head	Cube and Round
Weight	320 g (5 ton) and 448 g (7 ton)
Water depth	60 cm and 70 cm
Frequency	0.125–0.25
Amplitude	0.025–0.1 cm

During the assembly process, the number of innovative tetrapods in each color zone is recorded to determine the number of modified tetrapods installed. Afterward, when the testing process has been completed, the number of modified tetrapods is calculated using the number of modified tetrapods in the wave run-up and run-down areas. The calculation results are then multiplied by 100% to get the percentage of damage that occurred. The fixed weight of the rod is calculated using the Hudson Equation, as shown in Equation (4).

$$W = \frac{wH}{Kd(Sr-1)3\cot(\theta)} \tag{4}$$

where, W = Weight of the armor unit, H = Design wave height, K_D = Stability coefficient, θ = Angle of inclination of the structure, Sr = Relative specific gravity (a/w), a = Specific gravity of the Armor unit, and w = Specific gravity of water. From the Hudson formula, the K_D value can be determined. Wave height data was recorded to determine the relationship between wave height and the amount of damage to the protective layer unit (tetrapod). The displacement of the tetrapod defines damage. Other visual observations during testing are carried out, such as the position of the calm water surface towards the protective layer unit, the occurrence of overtopping waves, the shape of waves hitting the breakwater, and the condition of damage to the protective layer.

A breakwater model declared feasible will be accepted if it does not exceed the limits set by the planner or commonly used standards. If the research results exceed the feasibility limits, then the design must be re-planned. The feasibility limits standards for the breakwater model are defined in **Table 5**.

Table 5. Feasibility limits of the protective layer model.

Testing	Detail of Parameters	Information
Stability	Damage ≤ 0.5% on H	PT. Semen Gresik Standard (1991)
Protective	Damage ≤ 5% on H	CERC Standard (1984)
Layer	Damage ± 2.5% on H	Van der Meer Standard (1987)

3. Results and discussion

The analysis was carried out by graphing the relationship between the parameters of the measurement results and the relationship between dimensionless parameters, such as wave steepness H/gT2, and other essential parameters, such as the K_D stability number and the level of damage in %. This graph is intended to show the influence of height and wave period on the K_D value and level of damage. The data above contains the number of modified tetrapods that experienced a shift in position and its relationship with other data from other researchers. Meanwhile, if no modified tetrapods experience movement or changes in position, it is considered stable. The data above is then presented in graphical form; parameters such as level of damage (%) and wave steepness are sorted from small to large, then the paired parameters are adjusted to the same as the original data (before sorting).

3.1. Experiment result

The experiment result example with some scenarios showed the damage in the breakwater, as seen in **Figure 6**. Experimental damage is when the tetrapod innovation moves from the original position or gets cracked or fractured.

Figure 6. Damage experiment result.

During testing, wave data and data from visual observations of the Innovative Tetrapod armor unit's stability test were used as a reference in creating several graphs of the relationship between dimension parameters and dimensionless parameters. Making graphs will make it easier to answer the problem formulation raised in this research. This research shows the relationship between essential parameters that have a significant and vital correlation, including the level of failure (%), stability coefficient (K_D), wave height (H), and wave steepness (H/gT2). The relationship is presented below.

3.1.1. Level of failure (%) vs. wave height

The graph defining the level of failure (%) vs. wave height shows the result from **Figures 7–10**.

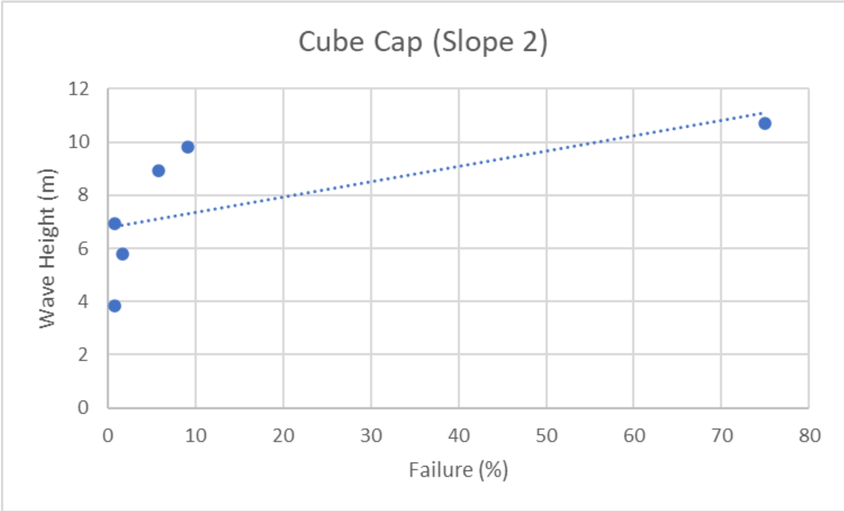


Figure 7. Level of failure vs. wave height for cube-caped innovative tetrapod with slope 1:2.

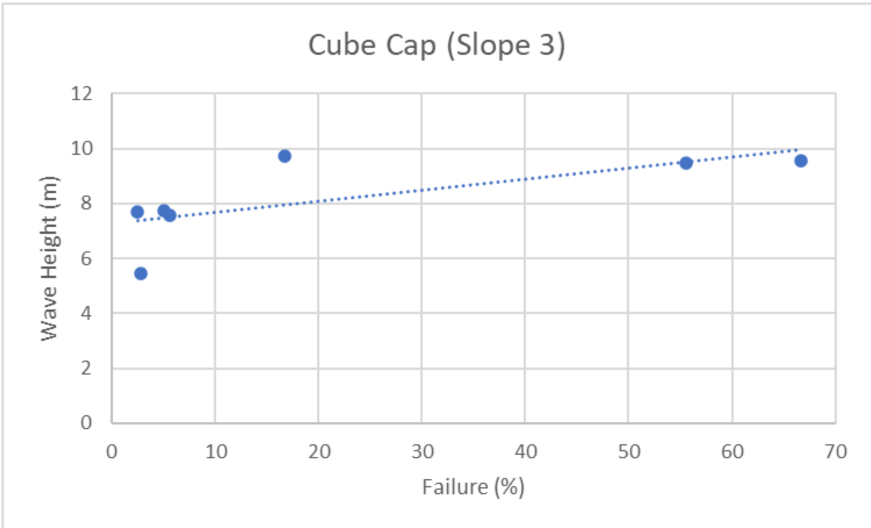


Figure 8. Level of failure vs wave height for cube-caped innovative tetrapod with slope 1:3.

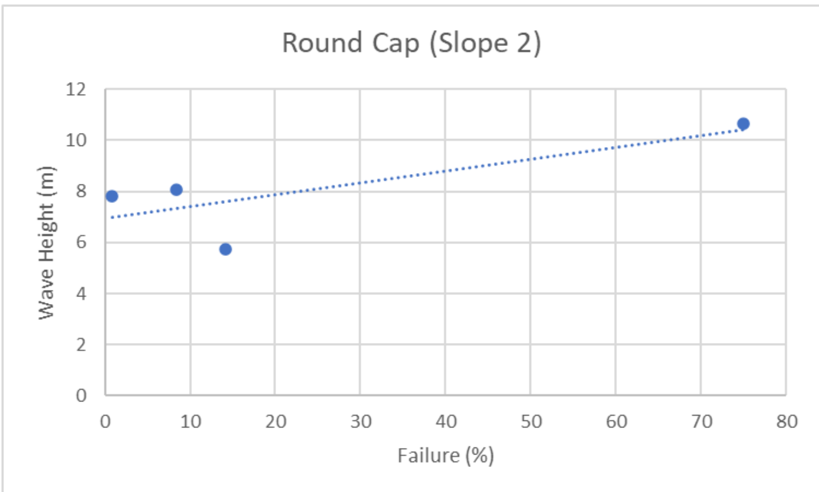


Figure 9. Level of failure vs wave height for round-caped innovative tetrapod slope 1:2.

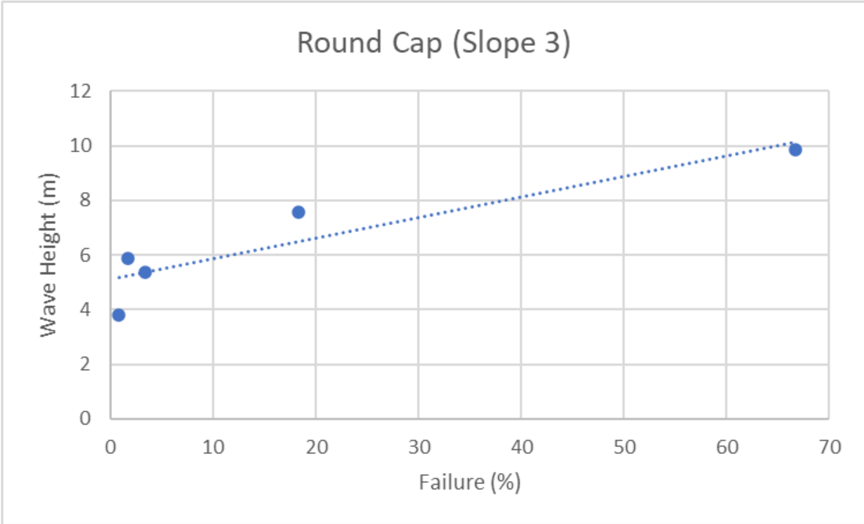


Figure 10. Level of failure vs wave height for round-caped innovative tetrapod slope 1:3.

From **Figures 7–10**, it is shown that for all variations in the slope of the model face, variations in the weight of the test object, and variations in the shape of the cap, the greater the wave height, the greater the level of damage, with different damage rates.

3.1.2. Stability coefficient (K_D) vs. level of failure (%)

The graph's result for defining the stability coefficient (K_D) vs. the level of failure (%) is shown from **Figures 11–14**.

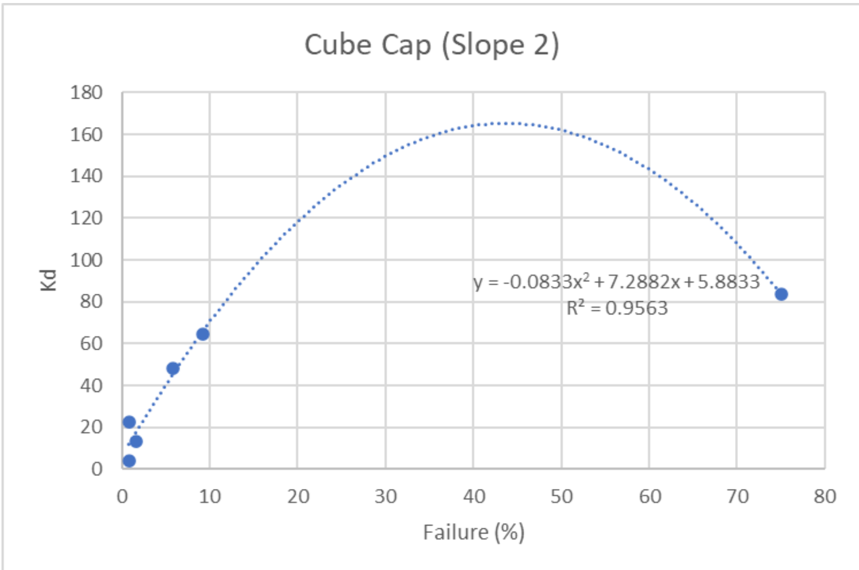


Figure 11. Stability coefficient vs failure for cube-caped innovative tetrapod with slope 1:2.

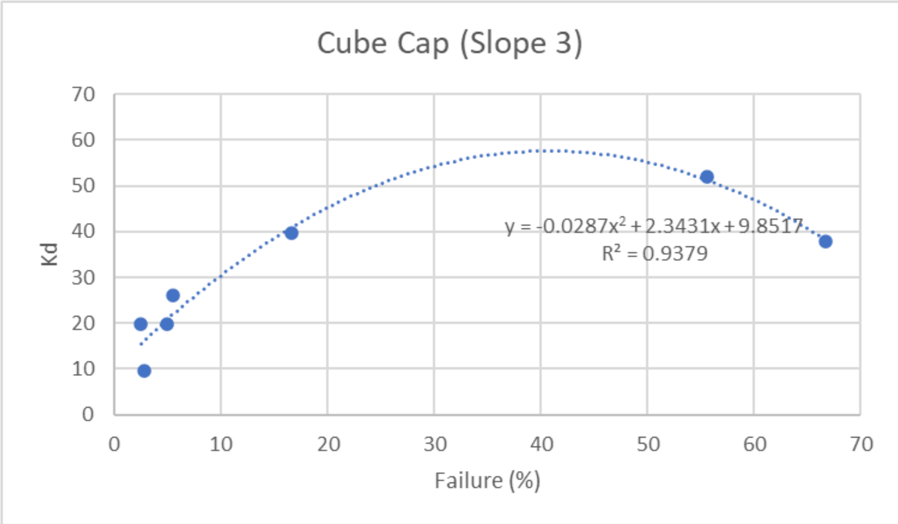


Figure 12. Stability coefficient vs failure for cube-caped innovative tetrapod with slope 1:3.

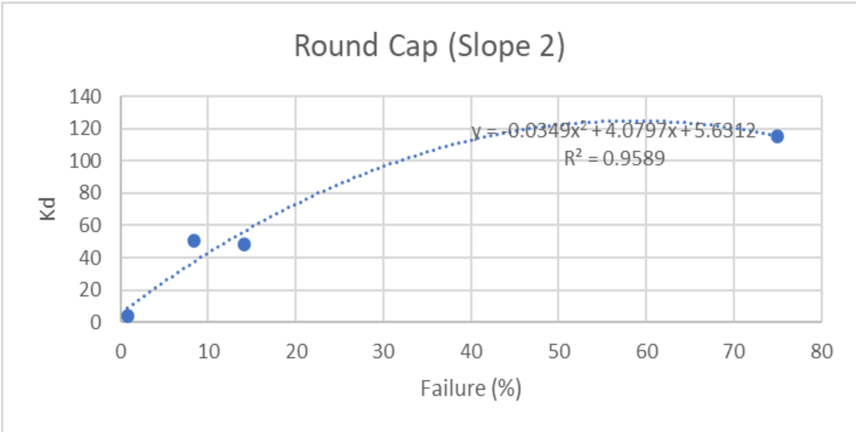


Figure 13. Stability coefficient vs failure for round-caped innovative tetrapod with slope 1:2.

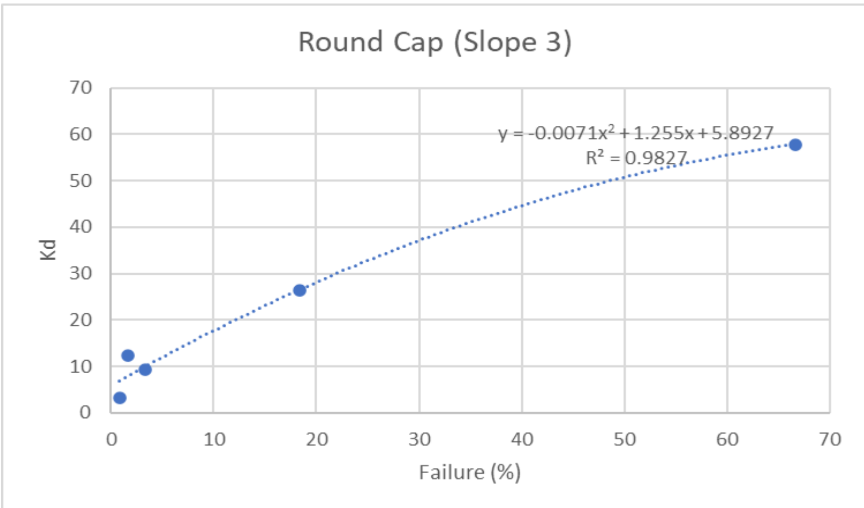


Figure 14. Stability coefficient vs failure for round-caped innovative tetrapod with slope 1:3.

Figure 11 with slope 1:2 shows that the greater K_D, the greater the number of failures. At the peak point, with the value of K_D almost reaching 160, the number of failures is greater than 40%, so the stability coefficient decreases with a more significant level of failure. The equation can be used to determine the value of the coefficient $K_D = y = -0.0833x^2 + 7.2882x + 5.8833$. Compared with slope 3, the K_D coefficient is more minor, indicating that the experiment agrees with **Table 1**.

3.2. Stability coefficient analysis

A curve equation is obtained for each test result from the regression analysis results. Based on this equation, the K_D value can be found for the acceptable level of damage, namely 0.5% (PT. Semen Gresik Standard (1991), 2.5% (United States. Army. Corps of Engineers, 1984) and 5% (Van der Meer, 1987). The results are shown in **Table 6**. Then, the recommended KD values for each round, cube cap, and slope are calculated by averaging. The stability coefficient result can be seen in detail in **Table 6**.

Table 6. Summary of the stability coefficient for all scenarios.

Slope	Type	Damage (%)	K_D	K_D Average	Equation
2	Cube	0.5	9.51	24.44	$y = -0.0833x^2 + 7.2882x + 5.8833$ $R^2 = 0.96$
		2.5	23.58		
		5	40.24		
	Round	0.5	7.66	16.14	$y = -0.0349x^2 + 4.0797x + 5.6312$ $R^2 = 0.96$
		2.5	15.61		
		5.0	25.16		
3	Cube	0.5	11.02	15.8	$y = -0.0287x^2 + 2.3431x + 9.8517$ $R^2 = 0.94$
		2.5	15.53		
		5.0	20.85		
	Round	0.5	6.52	9.16	$y = -0.0071x^2 + 1.255x + 5.8927$ $R^2 = 0.98$
		2.5	8.99		
		5.0	11.99		

From **Table 6**, the cube-caped shape provides an average K_D from 9 to 40 with an average K_D value of 24 for damage 0.5%–5% with slope 1:2. This value has a slightly more excellent stability coefficient value than slope 1:3. The value agrees with the value of K_D for tetrapod as shown in **Table 1**. The cube-shaped shape shows a higher K_D than the round-shaped one. This means that to obtain proper and acceptable stability, the cube-capped shape requires a lighter tetrapod stone than the innovative tetrapod with a round-capped shape. The modified tetrapod design has a higher K_D value than the conventional one. The cube-shaped tetrapod is recommended for its excellent K_D value compared to the round shape. As wave height increases, so does the level of damage, as seen in the steepness of the graph. This trend is consistent across variations in revetment face slope, specimen weight, and cap shape.

4. Conclusion

The modified innovative tetrapod showed a more excellent K_D value than the conventional design. The cube-shaped shape has a recommended K_D value greater than the round shape. This means that for the modified tetrapod structure and the same level of security, the required weight of the tetrapod with the cube cap will be lighter than the tetrapod with the round cap. For all variations in the slope of the revetment face, variations in the weight of the specimen model, and variations in the cap shape, the trend shows that the greater the wave height (H), the greater the level of damage (%), with different damage rates (seen from the steepness of the graph). This shows the same phenomenon as in the field.

Authors contributions: Conceptualization, NNP and IMAP; data curation, AY, KGPA and GRPAS; formal analysis, NNP and MSIBI; funding acquisition, NNP; methodology, NNP and IMAP; project administration, NNP and AY; resources KGPA and GRAPAS; validation, MSIBI; visualization, IMAP, AY, KGPA and GRPAS; writing original draft, NNP and IMAP; review and editing, NNP and MSIBI. All authors agreed to the published version of the manuscript.

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