Laboratory Physical Modeling of Rakuna IV Armor Block Stability and Overtopping Discharge of Patimban Port’s Rubble Mound Breakwater

D C Istiyanto\textsuperscript{1}, E Cholishoh\textsuperscript{2}, C Murtiaji\textsuperscript{2}, A B Widagdo\textsuperscript{2}, C I Sukmana\textsuperscript{2}, A Hamid\textsuperscript{2}, E A Wiguna\textsuperscript{2}, A S D Marta\textsuperscript{2}, J Setiawan\textsuperscript{2}, and B Santosa\textsuperscript{2}

\textsuperscript{1} Center of Technology for Maritime Industrial Engineering, Agency for the Assessment and Application of Technology, Tech. Bldg#2 PUSPIPTEK, Setu Tangerang Selatan 15314 - Indonesia
\textsuperscript{2} Port Infrastructures and Coastal Dynamic Technology Laboratory, Agency for the Assessment and Application of Technology, Jl Grafika 2 Sekip, Yogyakarta 55281 - Indonesia
Corresponding author: dinar.catur@bppt.go.id

Abstract. A series of 2D physical model experiment was carried out to examine the potential advantage of Rakuna IV armor block over Tetrapod blocks in term of stability, number of blocks for the same cross-section and overtopping discharge under predetermined experiment conditions. For the sea side slope armor, Rakuna IV–2ton armor blocks perform advantageous stability in comparison to Tetrapod-2ton blocks for the case of $H_w=1.2 \times H_s$. For the harbor side slope armor and toe armor, rocks of 300-1000kg/pc performs high stability with very less damage, with $S \ll 2$ and $S=0.11$ respectively ($S=2$ is initial damage condition). For the crest elevation $+2.5\text{mCD}$, overtopping discharge over either Rakuna IV or Tetrapod armored slopes are more or less at the same amount and both are still within allowed criteria limit. For the crest elevation $+2.1\text{mCD}$, overtopping discharge over Rakuna IV is still within allowed criteria limit. Reduction of breakwater crest from $+2.5\text{mCD}$ to $+2.1\text{mCD}$ (Rakuna IV) has relatively increased overtopping discharge four times higher, but it is still within allowed criteria limit. For the present experimental design, Rakuna IV armor layer is requiring less number of fabricated blocks for the same cross-section compared to Tetrapod block.

1. Introduction

1.1. Background, objective and scopes
The Port of Patimban, which is located in the northern coast of Subang Regency of West Java, is under construction since 2019. During the Detailed Engineering Design process, Rakuna IV armor block was proposed to use for the rubble mound breakwater armor layer. In order to investigate the hydraulic stability performance of Rakuna IV as well as the effect of breakwater crest elevation reduction on overtopping discharge over the breakwater, a series of laboratory hydraulic physical modeling was carried out. The objectives and scopes of these 2D physical model experimental series include the examination of the stability of typical design cross-sections armors protecting the seaward and rear slopes and toe under High water level (HWL + SLR) condition, the stability of toe under Mean Lower Low Water level, the wave overtopping under High water level (HWL + SLR) condition, and the
potential advantage of Rakuna IV over Tetrapod blocks in term of stability, number of blocks for the same cross-section and overtopping discharge under the present experiment conditions.

1.2. Test conditions
The test condition is shown in the following table 1.

| ID | Test armor | Conditions | Water level (mCD) | Breakwater crest (mCD) | Prototype H\textsubscript{mo} (m) | Prototype T\textsubscript{p} (s) | Considering factor | Remark |
|----|------------|------------|-------------------|------------------------|-----------------------------|-----------------------------|-----------------|--------|
| 1a | Rakuna IV, 2ton | 100 RP waves, High water + SLR (Northeast breakwater) | +1.65 | +2.5 | 1.8 | 6 | Rear and front slope stability | H\textsubscript{mo} = 1.2 \times H\textsubscript{L} WL = HWL + SLR |
| 1b | Rakuna IV, 2ton | 100 RP waves, High water + SLR (Northeast breakwater) | +1.65 | +2.5 | 1.5 | 6 | Rear and front slope stability | H\textsubscript{mo} = H\textsubscript{L} WL = HWL + SLR |
| 1c | Rakuna IV, 2ton | 100 RP waves, High water + SLR (Northeast breakwater) | +1.65 | +2.5 | 1.5 | 6 | Overtopping limit \(50 \text{ l/s/m}\) | H\textsubscript{mo} = H\textsubscript{L} WL = HWL + SLR |
| 2a | Rakuna IV, 2ton | 100 RP waves, High Water + SLR (Northeast breakwater) | +1.65 | +2.1 | 1.8 | 6 | Rear and Front Slope stability | H\textsubscript{mo} = 1.2 \times H\textsubscript{L} WL = HWL + SLR |
| 2b | Rakuna IV, 2ton | 100 RP waves, High Water + SLR (Northeast breakwater) | +1.65 | +2.1 | 1.5 | 6 | Rear and Front Slope stability | H\textsubscript{mo} = H\textsubscript{L} WL = HWL + SLR |
| 2c | Rakuna IV, 2ton | 100 RP waves, High Water + SLR (Northeast breakwater) | +1.65 | +2.1 | 1.5 | 6 | Overtopping limit \(200 \text{ l/s/m}\) | H\textsubscript{mo} = H\textsubscript{L} WL = HWL + SLR |
| 3a | Tetrapod, 2ton | Max 100 RP waves, High Water + SLR (Northeast breakwater) | +1.65 | +2.5 | 1.8 | 6 | Rear and Front Slope stability | H\textsubscript{mo} = 1.2 \times H\textsubscript{L} WL = HWL + SLR |
| 3b | Tetrapod, 2ton | 100 RP waves, High water + SLR (Northeast breakwater) | +1.65 | +2.5 | 1.5 | 6 | Overtopping limit \(50 \text{ l/s/m}\) | H\textsubscript{mo} = H\textsubscript{L} WL = HWL + SLR |
| 4 | Rakuna IV, 2ton | 100 RP waves, Low Water (West breakwater) | +0.22 | +2.5 | 1.8 | 6 | Toe stability | H\textsubscript{mo} = 1.2 \times H\textsubscript{L} WL = Mean LLWL |

Note: SLR – Sea Level Rise (=0.4m), HWL – High Water Level; RP – Return period; LLWL – Lower Low Water Level

In general, the maximum wave in the design wave train (=1.2\times H\textsubscript{L}) is used for slope and toe stability investigation, while overtopping check is carried out with design significant wave height (H\textsubscript{L}). Due to the importance of Patimban Port, no block displacement is assumed under the design wave conditions (i.e. under H\textsubscript{L}), however less than 1% displacement is allowed under overload wave (i.e. under H\textsubscript{max}). Degree of damage for all stability checks for front slope will be N\textsubscript{ed} = 0.3 (equivalent to 1% damage). The rear slope stability is checked against damage level parameter S\textsubscript{d}, which is defined as the number of cubic stones with a side of D\textsubscript{g0} eroded within a wide strip of the structure [1]. All the tests were carried out under non-breaking irregular waves (of JONSWAP spectrum) where the number of storm waves for each test is N = 1000 waves. Each test condition was repeated twice to allow any possible variation of damage due to wave randomness (a total of 9 test cases \(\times 2 = 18\) runs).

The selected test section for experiment is section A-A (northeast breakwater) and section B-B (west breakwater) of the following layout plan of Patimban Port in figure 1(a). The cross-section for each test condition were depicted in figure 1(b) to 1(e).
Figure 1. The selected test sections for experiment, section A-A (northeast breakwater) and section B-B (west breakwater) of Patimban Port.

Table 2. Model length scale calculation results.

| Armor Type | Volume of 2ton (m$^3$) | Density of miniature (g/cm$^3$) | Volume of miniature (cm$^3$) | Weight of miniature (g) | Number of Scale ($N_L$) |
|------------|------------------------|---------------------------------|-----------------------------|------------------------|------------------------|
| Rakuna IV  | 0.924                  | 2.300                           | 26.83                       | 61.72                  | 32.5                   |
| Tetrapod   | 0.8                    | 2.1326                          | 31.6                        | 67.41                  | 29.4                   |
2.2. Calculation of scale for corrected wave condition in experiment for armor unit stability

Due to difference between the density of concrete for actual site and the density of Rakuna IV and Tetrapod miniature, recalculation of the scale to correct the wave condition is carried out based on Hudson's formula (relation between wave height and weight of block). Relation between wave height and weight of block in Hudson's formula is shown as follows [3]:

$$M = \frac{\rho_c \cdot H^3}{K_d^3 \left(\frac{\rho_c}{\rho_w} - 1\right)^3 \cot \alpha}$$

(5)

in which $M$ = Weight of block (ton), $\rho_c$ = density of concrete (t/m$^3$), $\rho_w$ = density of water (t/m$^3$), $H$ = wave height (m), $K_d$ = number of stability and $\alpha$ = slope angle. If the scale factor “N” is included in the Hudson's formula it become as follows:

$$\left(NM\right)^3 = \frac{(N\rho_c) \cdot (NH)^3}{(N\Delta)^3}$$

(6)

where $N_M$ = Scale of "M", $N_{pc}$ = Scale of "pc", $N_\Delta$ = Scale of "(\rho_c/\rho_w-1)", $N_H$ = Scale of "H". Here no scale-change for $K_d$ and $\alpha$ (certain value).

Rearranging the above written Equation (3), the scale of corrected wave condition in the experiment for block stability can be calculated as follows:

$$\left(NH\right)^3 = \frac{(NM)^3 \cdot (N\Delta)^3}{(N\rho_c)}$$

(7)

For this calculation, related data for each type of block are shown in table 3.

| Table 3. Data for the calculation of wave height model scale. |
|-------------------------------------------------------------|
|                Density of concrete (t/m$^3$) | Density of seawater (t/m$^3$) | Volume of 2ton block (m$^3$) | Weight of block (t) |
| Rakuna IV       | Actual site 2.400 | 1.025 | 0.924 | 2.2176 |
|                 | Miniature 2.300 | 1.025 | 26.83 | 61.72 |
| Tetrapod        | Actual site 2.400 | 1.025 | 0.8 | 1.92 |
|                 | Miniature 2.1336 | 1 | 31.6 | 67.41 |

By applying equation (7) and data in table 3, the modified scale of wave model due to difference of concrete density for the actual site and miniature of Rakuna IV is found to be 1/33.6, whereas the length scale according to the Rakuna IV miniature calculation is 1/32.5. Finally, the scale of 1/32.5 is selected for both miniature or wave model either by consideration that using this scale gives more safety side for wave condition in comparison to the 1/33.6.

Further, for the case of Tetrapod armor layer, the modified scale of wave model due to difference of concrete density for actual site and miniature of Tetrapod is 1/34.8, whereas the length scale according to the Tetrapod miniature scale calculation is 1/29.4. Since the model wave height difference between these scales (1/29.4 and 1/34.8) is reasonably high, i.e. 0.80 - 0.95 cm, the scale of corrected wave condition in the experiment of Tetrapod stability is finally taken at 1/34.8.

The other parts of breakwater section are scaled down according the relevant scale of miniature for each series test condition. Based on the results of model scale calculation, the model test conditions are shown in table 4.

2.3. Quantity of armor blocks for the front (sea) slope

The quantity of armor block per unit length of breakwater is calculated by the following formula:

$$N = \frac{V \times (1-\alpha)}{v}$$

(8)
where \( N \) is quantity of armor block per unit length of breakwater (nos), \( V \) is volume of armor layer per unit length, \( \alpha \) is void ratio (50\% for Tetrapod and 56.5\% for Rakuna IV), and \( \upsilon \) is concrete volume of one armor unit. The volume \( V \) per unit length is equal to the cross-section area of armor layer, while the total volume is the product of cross section area multiply by the breakwater length in concern.

The calculation results of armor blocks quantity for each of cross section model is shown in table 5.

| Table 4. Model test conditions. |
|--------------------------------|
| ID | Test armor | Front slope armor units (nos) | Water level (mCD) | Breakwater crest | Prototype | Corrected model wave | Scale N | Considered factor | Remarks |
|----|------------|-----------------------------|------------------|-----------------|------------|---------------------|------|------------------|---------|
| 1a | Rakuna IV, 2ton | 230 | +1.65 | +2.5 | 1.8 | 6 | 5.5 | 1.1 | 32.5 | Rear and front slope stability |
| 1b | Rakuna IV, 2ton | 230 | +1.65 | +2.5 | 1.5 | 6 | 4.6 | 1.1 | 32.5 | Rear and front slope stability |
| 1c | Rakuna IV, 2ton | 230 | +1.65 | +2.5 | 1.5 | 6 | 4.6 | 1.1 | 32.5 | Overtop, limit of 50 l/s/m |
| 2a | Rakuna IV, 2ton | 220 | +1.65 | +2.1 | 1.8 | 6 | 5.5 | 1.1 | 32.5 | Rear and front slope stability |
| 2b | Rakuna IV, 2ton | 220 | +1.65 | +2.1 | 1.5 | 6 | 4.6 | 1.1 | 32.5 | Rear and front slope stability |
| 2c | Rakuna IV, 2ton | 220 | +1.65 | +2.1 | 1.5 | 6 | 4.6 | 1.1 | 32.5 | Overtop, limit of 200 l/s/m |
| 3a | Rakuna IV, 2ton | 287 | +1.65 | +2.5 | 1.8 | 6 | 5.2 | 1.0 | 29.4 | Rear and front slope stability |
| 3b | Rakuna IV, 2ton | 287 | +1.65 | +2.5 | 1.5 | 6 | 5.1 | 1.1 | 29.4 | Overtop, limit of 200 l/s/m |
| 4  | Rakuna IV, 2ton | 156 | +0.22 | +2.5 | 1.8 | 6 | 5.5 | 1.1 | 32.5 | Toe stability |

Note: SLR – Sea Level Rise (=0.4m), HWL – High Water Level; RP – Return period; MLLWL – Mean Lower Low Water Level

| Table 5. Calculation results of total armour block required. |
|------------------------------------------------------------|
| Cross-section | Armor tested      | Breakwater crest (mCD) | A (m²) | NL | Volume (cm³) | Porosity (%) | Width of flume (cm) | Total unit |
|----------------|-------------------|-----------------------|--------|----|-------------|--------------|-------------------|------------|
| I              | Rakuna IV         | +2.5                  | 29.92  | 32.5 | 26.83       | 56.5         | 50                | 230        |
| II             | Rakuna IV         | +2.1                  | 28.72  | 32.5 | 26.83       | 56.5         | 50                | 220        |
| III            | Tetrapod          | +2.5                  | 31.35  | 29.4 | 31.60       | 50.0         | 50                | 287        |
| IV             | Rakuna IV         | +2.5                  | 20.33  | 32.5 | 26.83       | 56.5         | 50                | 156        |

An additional example of calculation results of armor blocks quantity, comparison between Tetrapod and Rakuna IV, at the same length scale (\( N_l = 20 \)) for 100 m³ of prototype area is displayed in table 6. It provides more clear illustration on the potential different numbers between Rakuna IV and Tetrapod armor blocks for the same cross-section.

| Table 6. Calculation results of total armor unit for the same length scale. |
|---------------------------------------------------------------|
| Armor type | Prototype Volume of 2ton (m³) | A (m²) | Porosity (%) | \( N_l \) | V (cm³) | Width of flume (cm) | Total unit |
|------------|--------------------------------|--------|--------------|--------|--------|-------------------|------------|
| Rakuna IV  | 0.9240                         | 100    | 56.5         | 20     | 115.5  | 100               | 942        |
| Tetrapod   | 0.8000                         | 100    | 50.0         | 20     | 100.0  | 100               | 1,250      |

From the calculation results in table 5 and the illustration calculation results in table 6, it is known that the required number of Rakuna IV armor blocks is less about 20\% to 25\% than Tetrapod.
2.4. Experimental setup layout
The 2D experiments were conducted in the wave basin of Harbor Infrastructure and Coastal Dynamics Technology Laboratory (BTIPDP) of the Agency for the Assessment and Application of Technology (BPPT) at Yogyakarta, Indonesia. A wave flume of 6.1 m length, 0.5 m width and 0.7 m height was constructed inside the basin to put breakwater model for running the experiments. Illustration of the experiment model setup inside the flume is depicted in figure 2.

Figure 2. Experimental flume setup in the basin of BTIPDP-BPPT Laboratory; (a) the situation view of flume construction inside the wave basin, (b) model setup in the flume.

2.5. Model construction and basic research test
Following the completion of the flume construction, an array of 3 (three) wave gauges were set up in the flume for wave data acquisition during experiment. The distances between gauges are determined to cover identification of wave reflection during model running. After completion of the flume setup, a series of wave generation were conducted as a basic research test to observe the wave generation performance in reference to the designed incident wave model. Figure 3(a) and 3(b) respectively shows situation photographs of wave gauge setting and wave flume performance checking. All dimensions of model cross-section, including elevation, width, thickness, etc. were accurately plotted and drawn on the flume walls. The core layer (rubble stone) were initially poured and gently compacted to match the drawn cross-section template. After that, the under layer then spread above it and continued with the armor blocks and armor rocks arrangement. Figure 3(c) and 3(d) shows the photographs of model arrangement preparation in the experimental flume.

Figure 3. Model construction and setup; (a) wave gauge setting; (b) wave flume performance checking; (c) plotting of breakwater cross-section on the flume wall; and (d) armor blocks and rocks placement.

3. Damage Criteria

3.1. Damage of concrete armor units
The damage of block slopes is evaluated through the damage number \( N_{od} \) as follows [3]:

\[
N_{od} = \frac{N_{o-mov}}{B/D_n} \quad (9)
\]

where \( N_{o-mov} \) is the total number of moved blocks in all considered modes, \( B \) is a considered length for damage assessment along the breakwater axis. 
\( N_{o-mov} \) is calculated as follows:
\[ N_{o\text{-mov}} = N_{o\text{-s}} + N_{o\text{-out}} + N_{o\text{-r}} \] (10)

Any unit that are displaced in the form of slide or disorientated from their initial positions over distances larger than 0.5\(D_n\), or with angles larger than 45\(^\circ\) (designated as \(N_{o\text{-s}}\)), extract from the slope (displaced distances > 2\(D_n\), \(N_{o\text{-out}}\)), or are seen rocking with large angles of rotation (> 45\(^\circ\)) (\(N_{o\text{-r}}\)) are all accounted for as moved ones.

Beside the damage criteria by \(N_{o\text{s}}\), the level of structure damage can also be classified based on the percentage of damage \(D\), which is defined as follows:

\[ D = \frac{N_{o\text{-mov}}}{N_o} \times 100\% \] (11)

where \(D\) is the damage percentage, \(N_o\) is the total number of units within the reference zone. The classification of model breakwater damage refers to [4].

3.2. Damage of rock slopes and toe

Damage evaluation of the rock (berm) slope was conducted based on the result of damage level \(S\) calculation, as defined in the following formulas [3].

\[ S = \frac{A_e}{D_{n50}} \] (12)

in which \(S\) is the relative eroded area or the damage level, \(A_e\) is the eroded cross-sectional area of the rock profile, and \(D_{n50}\) is the median nominal diameter of stone.

Determination of \(A_e\) (cm\(^2\)) is approached by the following formula:

\[ A_e = \left( \frac{D_{n50}^2 \times N_{mov}}{\phi} \right) \left( \frac{W}{D_{n50}} \right) \] (13)

\[ D_{n50} = \left( \frac{W_{50}}{\rho_r} \right)^{1/3} \] (14)

in which \(A_e\) is eroded cross-sectional area of the rock profile (average eroded cross-sectional area per a row of rock), \(D_{n50}\) is median nominal diameter (cm), \(N_{mov}\) is number of moved rock, \(\phi\) is density of rock=50\%, \(W\) is width of flume (cm), \(D_{n50}\) is median nominal diameter (cm), \(W_{50}\) is median weight of Rock (g), and \(\rho_r\) is density of rock (g/cm\(^3\)).

Based on the calculated damage level \(S\), damage of the rock slope is classified according to the manual of damage level for two-layer rock armor in [1, 3, 6].

3.3. Overtopping criteria

The average overtopping rate per unit length of breakwater (l/sec/m\(^3\)) over the test duration is calculated using the following formula [5]:

\[ q = \frac{V_{ovt}}{T_{ovt} \times W_{ch}} \] (15)

where \(V_{ovt}\) is the total collected overtopping volume, \(T_{ovt}\) is duration of overtopping measurement, and \(W_{ch}\) is inner-width of overtopping collector chute. The limit criteria of overtopping discharge related to damage to the defense crest or rear slope structure refers to [5].

4. Physical Model Test

4.1. Stability of armor units, armor rock, and toe

The positions of armor units, armor rock, and toe before and after experiment were recorded by photo camera, both for the front (sea) and rear (harbor) side of breakwater. A continuous recording by using video camera were also done for the front side view and for the side view (perpendicular to the breakwater cross-section) over the determined model running time. After each experiment series, the position of armor units, armor rock, and toe rock were visually observed to identify any movement and the situation were recorded into the available form. Before initiation of each experiment, it is ensured...
that every moved unit in the previous running had been put back to its original position (before attacked by waves).

4.2. Wave overtopping
Wave overtopping flow was collected by using gutter and container. The 20 cm inner-width gutter placed on the edge of rear side concrete crest of the breakwater to guide the overtopping flow into the container. The collected overtopped water in the container was then pumped outward into another bucket that already prepared at the measurement area. The volume of collected water was measured to calculate the average overtopping rate over the running time duration.

5. Summary of Experiment Results

5.1. Overall results summary
The overall experiment results are summarized in table 7 to describe its compliance to the damage limit criteria.

Table 7. Experiment results compliance to the limit criteria of the considered factors.

| ID | Test armor | Conditions | Water level (mCD) | BW crest (mCD) | Hmo (m) | Tp (s) | Considering factor (criteria) | Result | Note |
|----|------------|------------|------------------|----------------|---------|-------|--------------------------------|--------|------|
| 1a | Rakuna IV, 2ton | 100RP waves, High water + SLR (Northeast BW) | +1.65 | +2.5 | 1.8 | 6 | front slope stability (< 1%) | Hardly comply |
| 1b | Rakuna IV, 2ton | 100RP waves, High water + SLR (Northeast BW) | +1.65 | +2.5 | 1.5 | 6 | front slope stability (< 1% ) | Hardly comply |
| 1c | Rakuna IV, 2ton | 100 RP waves, High water + SLR (Northeast BW) | +1.65 | +2.5 | 1.5 | 6 | Overtopping (< 50 l/s/m ) | 26.95 l/s/m comply |
| 2a | Rakuna IV, 2ton | 100RP waves, High Water + SLR (Northeast BW) | +1.65 | +2.1 | 1.8 | 6 | front slope stability (< 1% ) | Hardly comply |
| 2b | Rakuna IV, 2ton | 100RP waves, High Water + SLR (Northeast BW) | +1.65 | +2.1 | 1.5 | 6 | front slope stability (< S=2) | Hardly comply |
| 2c | Rakuna IV, 2ton | 100RP waves, High Water + SLR (Northeast BW) | +1.65 | +2.1 | 1.5 | 6 | Overtopping (<200 l/s/m) | 119.48 l/s/m comply |
| 3a | Tetrapod, 2ton | Max 100 RP waves, High Water + SLR (Northeast BW) | +1.65 | +2.5 | 1.8 | 6 | front slope stability (< 1% ) | Slight (1% displaced) comply |
| 3b | Tetrapod, 2ton | 100 RP waves, High water + SLR (Northeast BW) | +1.65 | +2.5 | 1.5 | 6 | Overtopping (< 50 l/s/m) | 25.87 l/s/m comply |
| 4 | Rakuna IV, 2ton | 100 RP waves, Low Water (West BW) | +0.22 | +2.5 | 1.8 | 6 | Toe stability – front (< S=2) | Initial damage comply |

Note: SLR – Sea Level Rise (=0.4m), HWL – High Water Level; RP – Return period; BW – Breakwater
5.2. Armor units stability
The number of moved armor units in each experiment and the related damage classification [4] are summarized in table 8. It is shown that all $N_{rd}$ numbers in the present experiment are less than 0.3.

5.3. Armor rock stability
The present experiment resulted in no massive movement of armor rock rather several spots of single rock movement only. In this regard, the eroded cross sectional area was calculated according to the total area of moved rocks. Table 9 shows the summary of experiment data and damage calculation results of armor rock at the rear (harbor side) slope of breakwater. In this table 9, $N_{ri}$ means the model scale of incident wave. The armor rock damage is classified according to [1, 3, 6].

Table 8. Summary of moved armor units at the front (sea) side of breakwater.

| ID series | Tested armor | $H_{mo}$ (cm) | $T_p$ (s) | Slope | $N_{mov}$ | $N_{rd}$ | D (%) | Damage classification |
|-----------|--------------|---------------|-----------|--------|-----------|----------|-------|----------------------|
| 1A-1      | Rakuna IV, 2ton | 5.3           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 1A-2      | Rakuna IV, 2ton | 5.3           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 1B-1      | Rakuna IV, 2ton | 4.5           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 1B-2      | Rakuna IV, 2ton | 4.5           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 1C-1      | Rakuna IV, 2ton | 4.5           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 1C-2      | Rakuna IV, 2ton | 4.5           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 2A-1      | Rakuna IV, 2ton | 5.3           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 2A-2      | Rakuna IV, 2ton | 5.3           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 2B-1      | Rakuna IV, 2ton | 4.4           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 2B-2      | Rakuna IV, 2ton | 4.4           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 2C-1      | Tetrapod, 2ton  | 4.4           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 2C-2      | Tetrapod, 2ton  | 4.4           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 3A-1      | Tetrapod, 2ton  | 5.3           | 1.0       | 1:4/3  | 1         | 0.07     | 0.35  | Slightly             |
| 3A-2      | Tetrapod, 2ton  | 5.3           | 1.0       | 1:4/3  | 1         | 0.07     | 0.35  | Slightly             |
| 3B-1      | Tetrapod, 2ton  | 5.1           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |
| 3B-2      | Tetrapod, 2ton  | 5.1           | 1.1       | 1:4/3  | 0         | 0        | 0     | Hardly               |

Table 9. Experiment data and damage calculation results of the rear slope armor rock.

| ID series | Tested armor | $N_L$ | $N_{ri}$ | Slope | $H_{mo}$ (cm) | $T_p$ (s) | moved rock | average weight of rock (g) | $D_{avg}$ (cm) | $A_r$ (cm$^2$) | S | Damage classification |
|-----------|--------------|-------|----------|--------|---------------|-----------|------------|------------------------------|-----------------|-----------------|---|----------------------|
| 1A-1      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 5.3           | 1.1       | 1          | 18.93                        | 1.93            | 0.29            | 0.08 | Initial damage       |
| 1A-2      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 5.3           | 1.1       | 4          | 18.93                        | 1.93            | 1.14            | 0.31 | Initial damage       |
| 1B-1      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 4.5           | 1.1       | 7          | 18.93                        | 1.93            | 2.00            | 0.54 | Initial damage       |
| 1B-2      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 4.5           | 1.1       | 2          | 18.93                        | 1.93            | 0.57            | 0.15 | Initial damage       |
| 2A-1      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 5.3           | 1.1       | 1          | 18.93                        | 1.93            | 0.29            | 0.08 | Initial damage       |
| 2A-2      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 5.3           | 1.1       | 3          | 18.93                        | 1.93            | 0.86            | 0.23 | Initial damage       |
| 2B-1      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 4.4           | 1.1       | 3          | 18.93                        | 1.93            | 0.86            | 0.23 | Initial damage       |
| 2B-2      | Rakuna IV    | 32.5  | 32.5     | 1:1.5  | 4.4           | 1.1       | 2          | 18.93                        | 1.93            | 0.57            | 0.15 | Initial damage       |
| 3A-1      | Tetrapod     | 29.4  | 34.8     | 1:1.5  | 5.3           | 1.0       | 3          | 25.58                        | 2.13            | 1.16            | 0.26 | Initial damage       |
| 3A-2      | Tetrapod     | 29.4  | 34.8     | 1:1.5  | 5.3           | 1.0       | 3          | 25.58                        | 2.13            | 1.16            | 0.26 | Initial damage       |

5.4. Toe rock stability
The typical prototype of breakwater toe is constituted from the stones of 100–250 kg weight connected to the under layer rock with the same weight. The toe stability is assessed according to [1, 3, 6]. The experiment results are summarized in table 10.
Based on the experiment result, it is indicated that there is almost no mass movement of toe rock but only unit rock movement, which lead to the conclusion that hardly scouring potentially exist.

5.5. Overtopping discharge
Volume of collected overtopping water during one experiment run is used to calculate average overtopping rate per unit length of breakwater (/sec/m)’ over the test duration. Calculation results of q (mean overtopping discharge) for all experiments are summarized in table 11.

| Table 10. Summary of experiment results of toe stability. |
| ID series | Tested armor | N_l | N_H | Slope | H_m0 (cm) | T_p (s) | moved rock | average weight of rock (g) | D_e0 (cm) | A_e (cm²) | S | Damage classification |
|-----------|--------------|-----|-----|-------|----------|--------|-----------|----------------------------|-----------|----------|---|----------------------|
| 4-1       | Rakuna IV    | 32.5| 32.5| 1:2   | 4.74     | 1.07   | 3         | 5.10                       | 1.24      | 0.23       | 0.15 | Initial damage       |
| 4-2       | Rakuna IV    | 32.5| 32.5| 1:2   | 4.74     | 1.07   | 0         | 5.10                       | 1.24      | 0.00       | 0.00 | Initial damage       |

| Table 11. Calculation results of mean overtopping discharge. |
| ID Series  | Prototype Crest level (mCD) | Experiment data (model) | Prototype |
|           |                           | Water volume (L) | Duration (min) | N_l | q (L/s/m) | q_{limit} (L/s/m) |
| 1C-2      | +2.5                       | 32.32           | 21             | 32.5 | 23.76     | 50                |
| 1C-3      | +2.5                       | 41.00           | 21             | 32.5 | 30.14     | 50                |
| 2C-1      | +2.1                       | 167.15          | 21             | 32.5 | 122.89    | 200               |
| 2C-2      | +2.1                       | 157.87          | 21             | 32.5 | 116.07    | 200               |
| 3B-1      | +2.5                       | 47.32           | 21             | 29.4 | 29.93     | 50                |
| 3B-2      | +2.5                       | 34.48           | 21             | 29.4 | 21.81     | 50                |

6. Conclusion and recommendation
The present conducted physical modeling has confirmed that the damage level of designed Rakuna IV armor block as well as armor rocks of Patimban Port’s breakwater against the designed wave height are still under the minimum limit of damage criteria. Either Rakuna IV–2ton or Tetrapod-2ton are both hardly damage against H_{m0}=H_s, but Rakuna IV–2ton perform advantageous stability in comparison to Tetrapod-2ton blocks for the case of H_{m0}=1.2×H_s. The rear slope armor rocks of 300-1000kg/pc and the toe rocks of 100-250kg/pc performs very less damage (i.e. S << 2) under the initial damage condition (i.e. S=2). The mean overtopping discharge passed over the designed breakwater crest with elevation at +2.5mCD as well as the one at +2.1mCD, with Rakuna IV or Tetrapod armored slopes, both are still within allowed criteria limit either. For the present design, Rakuna IV armor layer also requires less number of fabricated blocks for the same cross-section in comparison to Tetrapod block. Rakuna IV armor blocks is suggested to use instead of Tetrapod since it performs advantageous stability and it reduces construction budget.

7. References
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