World Applied Sciences Journal 32 (3): 415-421, 2014
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2014.32.03.977

# Stability of Armour Layer under Wave Attack, 2-D Physical Model and Case Study in South Java Coastline, Indonesia

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**Abstract:** The stability of armour layer on the breakwater has been studied and the result is reviewed in this paper. By undertanding the stability of armour layer on the breakwater due to wave attack, it could minimize the breakwater damage and maximize the armour layer performance as a breakwater protector. The armour stability on composite breakwater has been investigated by 2-D physical model experiments using regular waves, combining with theoretical approach and field data application of South Java coastline, Indonesia. Tetrapods are used as armour layer for the breakwater. The breakwater model was placed inside a wave flume. The result shows that the level of damage was affected by wave characteristics of wave steepness. The steeper the wave steepness, the armour layer profile will change. It is shown by the percentage of the number of displacement and movement number of armour unit from its initial position, or armour layer damage under design wave. The results conclude that the results of physical models study can be used as a reference for the design of armour layer on breakwater.

**Key words:** Armour layer・2-D physical model・Wave height・Wave period

## INTRODUCTION

Indonesia is the second longest costline country in the world after Canada. However, most of these coastal area are prone to climate change as study showed that Coastal areas will be influenced the most by global warming [1]. Due to climate changes, the sea level is rising at an increased rate and storms substantially increase in intensity and duration [2]. The wave that coming from the sea has enormous amount of energy, that could eroded the unprotected coastline. Wave attack can be diminished by reducing this high energy of incoming wave so that, by the time this wave reach the shore line, it becomes low energy.

Common approaches applied to overcome coastal area problems (especially beach erotion), are *soft* approach and *hard* approach. *Soft* approach is the application of vegetation and beach nourishment [3]. While the *hard* approach is development of breakwater and revetment/seawall. The *soft* approach is more environmental friendly due to its low impact to the environment. However, in some coastal area with high wave height (*H*), *hard* approach is more effective to protect the beachline. Breakwater structure is applied to break and reflect the wave energy. In order to ensure breakwater structure fullfill its purpose, it is important to carefuly designing the breakwater. Also, to prevent failure or damage that could occurred under wave attack. The application of physical small scale model has been used for stability study of breakwater (Bruce *et al* [4] Verhaege *et al* [5] and Zanuttigh *et al* [6]). However only few combining the laboratory experiment result and field data verification as applied in current study.

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Fig. 1: Case study location of South Java coastline (red circle), Yogyakarta Province, Indonesia.


Fig. 2: Wave attack (a) and tetrapod displacement (b) occur at Breakwater in Glagah Beach (South Java coastline, Indonesia).

Therefore, the main objectives of this research are utilizing 2D-physical model combined with field data: (1) To get an optimum breakwater design, as a result of understand the stability of armour layer on breakwater due to wave attack and (2) To gain information regarding the behavior and stability of armour layer on breakwater due to the design wave or higher wave.

**Case Study in South Java Coastline:** In Indonesia, there are many failures of rubble mound breakwaters armoured with tetrapods and concrete unit. This condition caused by misplacement of armour units, thus there was also an inbalance between the strength (structural integrity) of the units and the hydraulic stability (resistence to displacements) of the armour layer. In this paper, case study presented are armour layer failure of breakwater armoured with tetrapods located in beach at south of Java island, Indonesia (Fig. 1). Figure. 2 shows failure of breakwater and seawall in south of Java Island Beach. This coastline facing enormous wave height ($H_s$). An evaluation was conducted upon this case. In this paper, research result of tetrapod armour layer on breakwater stability under wave attack is presented. Wave data utilized in this research is from South Java coastline, Indonesia.

## MATERIALS AND METHODS

**Theoretical Study**

**Linear Wave Theory:** By using of small amplitude wave theory, Airy derived the Laplace equation of irrotational current [7a]. After that he conducted linearization upon Bernoulli equation. It resulted the Airy wave theory or known as Linear wave theory. The calculation of Laplace equations are as follows:

- Sea water level $$\eta = \frac{H}{2}\cos(kx - \sigma t) \quad (1)$$
- Wave length $$L = \frac{g}{2\pi}T^2 \tanh\frac{2\pi}{L}h \quad (2)$$

**Standing Wave, Partial Standing Wave and Wave Run up:** Standing wave is combination of two waves of the same period and height but propagating in opposite directions where superimposed as one expects from the perfect reflection of an incident wave from vertical wall.

The total wave profile seaward of the obstacle is then with equation [7b]:

$$\eta_c = \eta_i + \eta_r = \frac{H_i}{2}\cos(kx - \sigma t) + \frac{H_r}{2}\cos(kx + \sigma t) \quad (3)$$

where $H_i = H_r$ so that:

$$\eta_c = H_i \cos(kx)\cos(\sigma t) \quad (4)$$

If $kx = n\pi$ where ($n=0,1,2,...$), maximum water surface fluctuation will be achieved at *antinodes*, if $kx = (n+1/2)\pi$ where ($n=0,1,2,...$), minimum water surface fluctuation will be achieved *anti nodes*. In partial standing wave, only some propagating wave are reflected $H_i > H_r$. However, wave period and wave length of reflected wave are similar to wave period and wave length. Wave system in (4) has become:

Wave system in (4) has become: $$\eta_c = \left(\frac{H_i}{2} + \frac{H_r}{2}\right)\cos(kx)\cos(\sigma t) + \left(\frac{H_i}{2} - \frac{H_r}{2}\right)\cos(kx)\cos(\sigma t) \quad (5)$$

If *nodes* and *antinodes* are considered as $H_t$ maximum and $H_t$ minimum, then:

$$\eta_{c_{maks}} = \frac{H_i + H_r}{2} \text{ and } \eta_{c_{\min}} = \frac{H_i - H_r}{2} \quad (6)$$

After eliminating the equation above, the result is:

$$H_i = \frac{H_{maks} + H_{\min}}{2} \text{ and } H_r = \frac{H_{maks} - H_{\min}}{2} \quad (7)$$

Victor *et al*. [8] was utilizing run-up parameter to study the relation between the relative percentage of run-up height versus probability of overtopping, studying the gap between slopes and breakwater stability.

Based on the experiment of equation *Ru* on smooth and impermeable slope with slope $\alpha$, Hunt[9] and Kobayashi [10], formulated that $R_u = \sqrt{H.L_o}\ \tan\alpha$, with, $L_o = \frac{g.T^2}{2\lambda}$ so that,

$$R_u = 0.4T\sqrt{gH\tan\alpha} \quad (8)$$

**Stability of Armour Due to Wave:** The performance of hydraulic structure to reduce wave force is influenced by these factors [11]:

- Wave characteristics, consist of water depth, wave period, wave height and wave length,
- Types of structure, including surface roughness and permeability,
- Structure geometry, such as slope, crest elevation relative to Sea Water Level (SWL) and width of crest.

Horikawa [12] studied that the magnitude of reflection from hydraulic structure is noted by reflection coefficient of $K_r$. as a comparison between reflection wave height ($H_r$) to the propagation wave height ($H_i$).The reflection coefficient is ranging $0 \le K_r \le 1$. This coefficient is used to calculate for wave height.

Armour stability on breakwater can be analyzed using Hudson [13] equation is as follows:

$$W = \frac{\gamma_r H^3}{K_D (S_r - 1) Cot(\theta)} \quad (9)$$

Some research regarding stability of armour layer under wave attack has been performed. Stability of rock protections and armour layer under wave attack can well be calculated by Van der Meer [14]. The placing of rock was described as a “dense pack” where every rock was placed individually by crane. Tests were performed with different blockness coefficients of the rock. Stewart *et al*. [15] performed an extensive research on packing densities, rock shape and the influence on stability and wave overtopping.

**Research Methods:** In order to fulfill the objectives of the research, this paper presented based on analysis result of Laboratory experiment (2-D) which was verified by field data of South Java Beach, Indonesia. Scheme of physical model 2-D and arrangement of tetrapod armour model can be viewed in Fig. 3 and 4, respectively. Preparatory works consist of development of prototype model inside wave flume, construction of tetrapods model and calibration process.

Calibration process was conducted upon wave generator devices called stroke and variation and wave probes. There were two aspects of wave generator device that was calibrated; they were wave height and period.

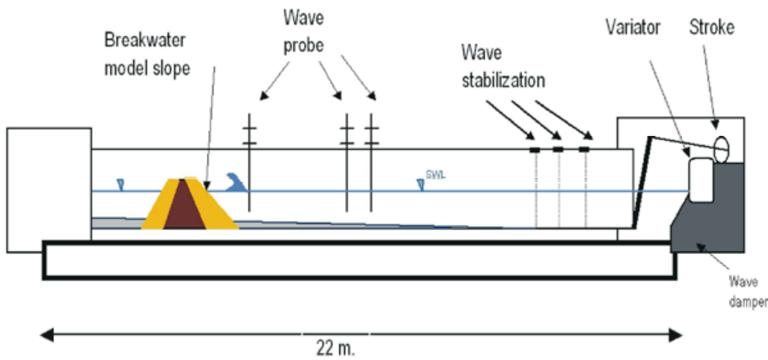


Fig. 3: Scheme of breakwater model inside wave flume

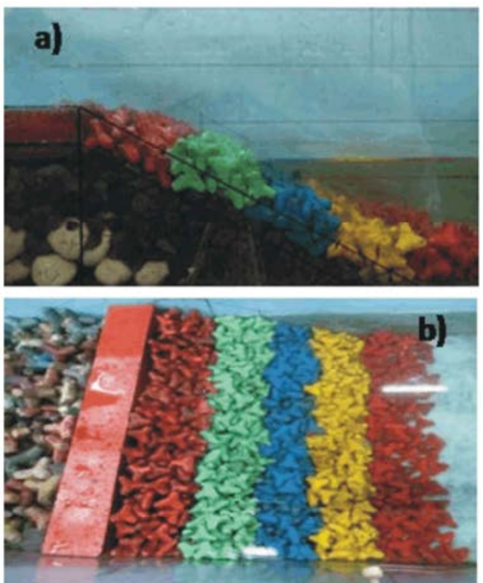


Fig. 4: Model of tetrapod armour layer on breakwater before wave attack; (a) side view and (b) above view

Table 1: Result of breakwater scale calculation (non distorted)

| Parameter | Calculation result<br>Prototype | Model | Scale | |
|---|---|---|---|---|
| Weight (W) | 14 T | 15.5 gr | $n_w$ | 903225,81 |
| Length (L) | 8 m. | 6.6 cm. | $n_L$ | 122 |
| Height (H) | 5,8 m. | 4.75 cm. | $n_H$ | 122 |
| Mass density (γ) | 2.4 T/m$^3$ | 1.99 T/m$^3$ | $n_l$ | 1,21 |
| Time (T) | 14 s. | 1.2 s. | $n_T$ | 11,04 |

Wave height was being adjusted by wave generator through stroke length. Wave period was modified by wave generator due to variation of rotation. Therefore, the adjustment of wave height and wave period was carried out during calibration process using (1), (2), (6) and (7).

**Geometry Scale:** Equation (9) was applied to calculate geometry scale of non distorted model. The result of calculation is $n_W = \frac{n_\gamma x (n_H)^3}{(n_B)^3} = 903225,81$

Hence scale of $n_L$ = 122. Recapitulate result of physical model scale calculation is shown in Table 1.

**Model Scale:** Calculation of Model scale consist of magnitude of wave height scale ($n_H$), length scale ($n$ ), depth scale ($n_d$), time scale ($n_t$), velocity scale ($n_V$) and mass density scale ($n_{\tilde{a}}$).

**Breakwater Model:** Prototype of breakwater utilized as a reference for developing a model of breakwater is breakwater located in, Glagah Beach, South Java, as shown in Fig. 5. The slope of model is 1:2, the weight of tetrapod (prototype) 14 T., with $\gamma_{concrete}$ = 2,4 T/m$^3$ [16]. In the model, crest height of breakwater from the base is 16.3 cm, width of breakwater is 6.6 cm. Tetrapod model is using concrete pre cast with the weight vary from 14.5 to 15.5 gr and mass density $\gamma_{concrete\ model}$ = 1.99 – 2.1 gr/ml.

**Wave Scale ($n_H$):** Based on the result of wave height calculation in South Java Coastline, the design wave height ($H_{100yr}$) is 5.8 m[16]. Physical model test was conducted in the wave flume using regular wave generator. Actually, wave in prototype is irregular wave. Hence, in order to replicate the real condition in nature, wave height should be divided using wave height scale (calculation result) and multiply by factor $Cw$ = 1.28. Calculation result of wave height in model found that for wave height of 5.8 m in prototype (actual condition in nature), wave height in model is 6.08 cm, also, this wave analogous with irregular wave.

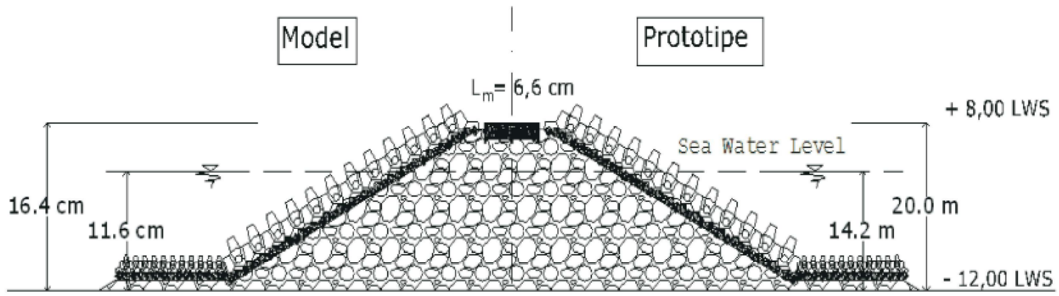


Fig. 5: Scheme prototype of breakwater VS, model of breakwater. [16]

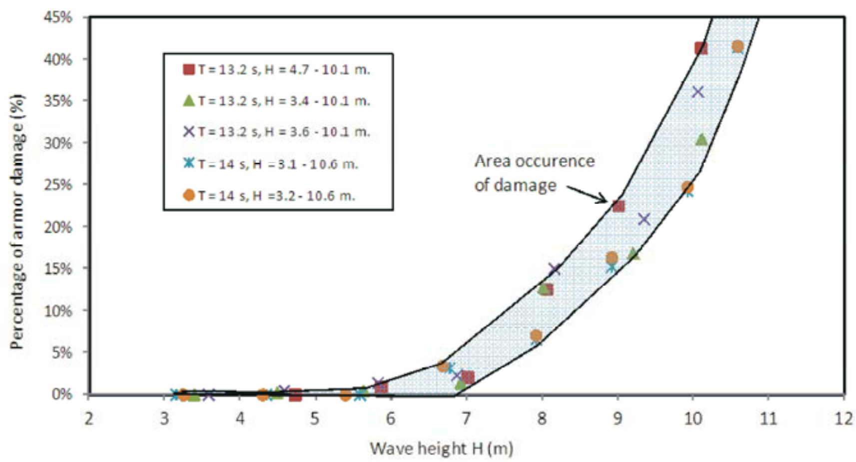


Fig. 6: Graph of relationship between wave height (*H*) and percentage of damage (%), with wave height and wave period of $H$ = 3.1 - 10.6 m. and T = 13.2 - 15.4 s, respectively.

## RESULT AND DISCUSSION

**Data of Wave Height and Wave Length:** Field measurement data was shown in the graph of relationship between wave height parameter compare to depth ($H/d$); and depth compare to wave length ($d/L$). Based on calculation of wave height, wave period, water depth and wave length, wave type can be determined. The wave type generated in this study, considering the relative depth value, is transitional wave type. Where relative depth ($d/L$) applied in all model ranging between $1/20 < d/L < 1/2$. The data distribution of wave shows that the wave data located in Airy wave in transitional sea area and few data located in Stoke's wave theory. Therefore, further calculation and analysis using Airy wave theory for transitional water depth area should be conducted.

**Damage of Armour Layer on Breakwater:** Analysis result of stable profile in 2-D physical model test was presented in Fig. 6. After that, percentage of damage was studied to obtain stability coefficient $K_D$ with wave height variation. The grouping of tetrapod stability condition analyzed based on wave height group with variation of wave period from $T$ = 13.2 seconds to $T$ = 15.4 seconds, also with variation of wave height of ($H$) = 3.1 m to 10.6 m. Analysis result of damage percentage grouping of tetrapod layer under wave attach can be seen in Fig 6.

From analyzing the percentage groups of tetrapod layer's damage (Fig. 6), the average percentage of damage with wave height and wave period of $H$ = 3.1 – 10.6 m. and $T$ = 13.2 – 15.4 second respectively is developed. Fig 6. also shows that percentage of damage is 41.6% under the wave height of $H$ = 10.6 m. The area of occurrence damage percentage is shown in Fig. 6.

After that, this analysis result was utilized to calculate tetrapod stability coefficient ($K_D$). Finally, the relationship between wave height $H$ and weight of tetrapod with variation of stability coefficient $K_D$ was studied, by using the graph in Fig. 7. The analysis result from running models show that the initial condition of armour failure is when tetrapods armour layer started to move or total damage occurred is 0,2%. From calculation result of the prototype, stability coefficient $K_D$ is 5.5., so that it analysis of $K_D$ which is used are $K_D$ = 4 – 8, respectively.

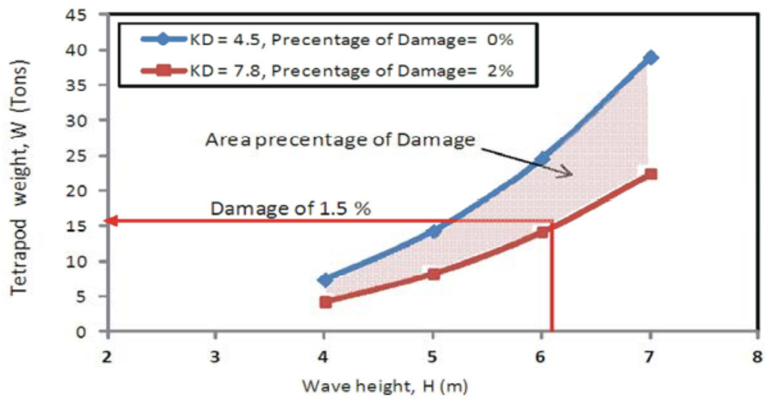


Fig. 7: Relationship between wave height $H$ and tetrapod weight, $K_D$ = 4.5and $K_D$ = 7.8, Percentage of damage is 0% and 2%.

Figure 7 shows $K_D$ without any armour layer damage is occurred at $H$ = 5 m. Then, calculation was conducted using Hudson equation. Calculation result shows $K_D$ without any damage is at $H$ = 4.5 m. Analysis result of tetrapods coefficient shown in Fig. 7. It shows that if design wave ($H_D$= 5,8 – 6.2 m) resulted in percentage of damage 0%, then tetrapod weight needed is 21 - 24 ton. Also, from this graph, it can be concluded that stability coefficient $K_D$ = 5.8 is achieved at wave height ($H$) = 6 m., tetrapod weight ($W$) = 15.8 Ton, when percentage of damage occurred is about 1.5%. Hence in Glagah beach, where the weight of tetrapod armour unit is 14Ton, it can be predicted that damage of < 2% will occur when wave height ($H$) = 5.8 m., $K_D$ = 5.5. Immediate repair work should be conducted to prevent further damage of breakwater.

## CONCLUSION

The results of Physical model tests are as follows:

- In order to obtain design wave for South Java Coastline area ($H_D$= 5,8 m. – 6.2 m.) with percentage of damage is 0%, required tetrapod weight is around 21 ton.
- From hydraulic model test, there were armour layer damages or displacement of 1.5% - 2% by utilizing tetrapod of 14 tons to 16 tons.
- The armour layer is still in good performance (the damage is being repaired instantly) considered good if design condition of wave height $H_D$ = 5.8 m – 6.2 m; and stability coefficient of armour ($K_D$) range is 4.5-7.8.
- The graphs developed from this research can be utilized as guidance to design a breakwater, especially in other areas that have similar wave characteristics (height and period) as in South Java coastline, Indonesia.
- Further theoretical study is needed to support stability analysis of armour layer on breakwater, especially with variation of armour stability coefficient $K_D$ and wave height.

## ACKNOWLEDGMET

The authors would like to acknowledge all the individuals of ‘The review design of Glagah Beach Breakwater Project, a collaboration project of Serayu-Opak Watershed Bureau, Ministry of Public Work and Center for Engineering Research Science, University of Gadjah Mada. Also, the authors would like to thank Head of Hydraulic-Hydrology Laboratory, Center for Engineering Research Science, University of Gadjah Mada and Director of Center for Engineering Research Science, University of Gadjah Mada for their enormous support in this research.

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