China Ocean Eng., 2017, Vol. 31, No. 6, P. 747–753
DOI: 10.1007/s13344-017-0085-3, ISSN 0890-5487
http://www.chinaoceanengin.cn/ E-mail: coe@nhri.cn

Placement Effect on the Stability of Tetrapod Armor Unit on Breakwaters in Irregular Waves

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Received April 7, 2016; revised March 7, 2017; accepted June 6, 2017

Abstract

Tetrapod, one of the well-known artificial concrete units, is frequently used as an armor unit on breakwaters. Two layers of tetrapod units are normmaly placed on the breakwaters with different placement methods. In this study, the stability of tetrapod units with two different regularly placement methods are investigated experimentally in irregular waves. Stability coefficients of tetrapod units for both placement methods are obtained. The important characteristic wave parameters of irregular waves causing the same damage ratio as those of the regular waves are also determined. It reveals that the average of one-tenth highest wave heights within the wave train ($H_{1/10}$) causes the similar damage as regular waves.

Key words: breakwaters, tetrapod unit, stability, placement methods, irregular waves

Citation: Çelikoğlu, Y., Engin, D., 2017. Placement effect on the stability of tetrapod armor unit on breakwaters in irregular waves. China Ocean Eng., 31(6): 747–753, doi: 10.1007/s13344-017-0085-3

1 Introduction

Concrete armor units are now widely used to protect breakwaters. In the past, several different unit shapes have been developed, such as tetrapod, dolos, accropode, tribar, and core-loc. The tetrapod unit was originally developed in 1950 by Sogreah Laboratory in France, as is a four-legged concrete structure to form a two-layer armor unit on breakwaters. The placement method of the tetrapod blocks on the armor layer is one of the important facts for breakwater stability. Tetrapods can be placed commonly with two different methods (see Fig. 1). Muttray and Reedijk (2008) stated that tetrapods can also be randomly placed. Normally two layers of tetrapods are placed as the armor layer for breakwaters. The difference of the placement in the upper armor layer distinguishing the two methods is shown in Fig. 1. The placement of tetrapods in the bottom armor layer for both methods are the same with one leg normal to and pointing outwards from the breakwater slope. The first placement method (inward-leg placement) is such that one leg of the tetrapod in the upper armor layer is directed inwards (upper layer) and is perpendicular to the breakwater slope (Fig. 1a). For the second placement method (upward-leg placement), the orientation of the blocks in the upper armor layer is identical to that of the first layer (Fig. 1b). The abbreviations of Method I and Method II are used in the following sections to represent the first placement method and the second placement method, respectively.

The stability of concrete armor units is described by several formulas, such as the formula of Hudson (1959) and the formula of van der Meer (1988). In all of these formulas, the stability of concrete units is expressed by the dimensionless stability number, $H_s/(\Delta D_n)$. Studies have been conducted to predict the stability number. According to Hudson formula, the stability number depends on the wave height, armor type, damage level and slope of the breakwater. Van der Meer (1988) considered type of breaker, permeability parameter, number of waves and surf similarity parameter for irregular waves in his formula. His formulas were obtained for a Rayleigh distribution of wave heights in deep water. However, breakwaters are commonly constructed in the intermediate or shallow waters, where the Rayleigh distribution may be not valid (Vidal et al., 2006). Therefore, van der Meer (1988) proposed to use $H_{2\%}$ (only 2% of the wave heights in the wave ray larger than this wave height) instead of the significant wave height in his cases.

In the past, several improvements on the stability formulas and the placement methods for tetrapod breakwaters were made by Meer and Heydra (1991), De Jong (1996), Gürer et al. (2005), Suh and Kang (2012).

The various stability formulas for tetrapod rubble mound breakwaters are summarized in Table 1. In these formulas, H_s is the significant wave height on the toe of the

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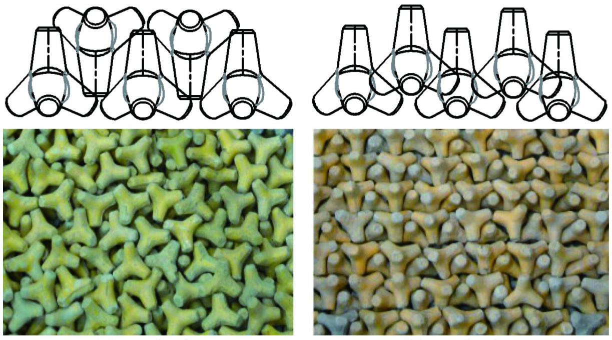


(a) Method I (b) Method II

Fig. 1. Placement methods for tetrapods.

breakwater; Δ (=ρ_a/ρ_w-1) is the relative mass density of each tetrapod unit; D_n is the nominal diameter (=M_a/ρ_a)$^{1/3}$; M_a is the mass of each tetrapod; ρ_a is the mass density of the tetrapods; ρ_w is the mass density of water; K_D is the stability coefficient; θ is the angle of structure slope; N_0 is the relative damage; $N_{0,\text{ mov}}$ is the total number of displaced and moved units; N is the number of waves; s_{om} is the wave steepness (=$2\pi H_s/(gT_m^2)$); T_m is the mean wave period; $\xi_z\left(=\tan\theta/\sqrt{s_{om}}\right)$ is the surf similarity parameter; R_c is the crest freeboard; and ϕ is the packing density.

Van der Meer and Heydra (1991) performed model tests on breakwater sections armored with tetrapods to study the strength of concrete armor units. In their study, not only units displaced out of the armor layer, but also more or less moving units were considered. Therefore they described three different damage types (N_0: number of units displaced out of the layer, N_0>0.5: number of units displaced larger than 0.5D_n; and N_0<0.5: number of units displaced smaller than 0.5D_n). Stability formula Eq. (3) in Table 1 shows that the number of displaced units is a function of wave height, steepness and storm duration, as is modified to describe the number of moved units.

De Jong (1996) investigated influence of the crest height and the packing density on the stability of tetrapods for plunging waves. However, the stability number is also a function of other parameters, such as unit shape, placement method, and slope angle.

Van den Bosch et al. (2002) investigated the influence of the density (porosity of armor layer) on the stability of tetrapods experimentally. Their experiments showed that the stability of the armor layer increased with the increasing density due to the placement. In other words, the stability increases with the decreasing porosity.

Gürer et al. (2005) investigated breakwaters with two different placement methods of tetrapod units in regular waves experimentally. The tests indicated that tetrapods units placed with Method II exhibites a slightly higher stability to the initial damage than those placed with Method I. However, the initial low level damage was followed by a rapid failure beyond a critical wave height. For Method I, failure occured gradually with the increasing wave height. They also defined the stability coefficients of the Hudson formula for the two placement methods.

Suh and Kang (2012) developed a new stability formula for tetrapod rubble mound breakwaters. They performed hydraulic model tests for different slope angles. Their results, together with the data of previous researchers, were applied

Table 1 Stability formulas for tetrapod rubble mound breakwaters

Author	Formula	Remarks	
Hudson (1959)	$\frac{H_s}{\Delta D_n}=(K_D\cot\theta)^{1/3}=f(\cot\theta)$	Regular waves; without period effect	Eq. (1)
Van der Meer (1988)	$\frac{H_s}{\Delta D_n}=\left[3.75\left(\frac{N_0}{\sqrt{N}}\right)^{0.5}+0.85\right]s_{om}^{-0.2}$	Irregular surging waves; slope 1:1.5; deep water conditions	Eq. (2)
Van der Meer and Heydra (1991)	$\frac{H_s}{\Delta D_n}=\left[3.75\left(\frac{N_{0,\text{mov}}}{\sqrt{N}}\right)^{0.5}+0.85\right]s_{om}^{-0.2}-0.5$	Irregular waves; slope 1:1.5; with influence of moving units	Eq. (3)
De Jong (1996)	$\frac{H_s}{\Delta D_n}=\left[8.6\left(\frac{N_0}{\sqrt{N}}\right)^{0.5}+3.94\right]s_{om}^{0.2}$	Irregular plunging waves; slope 1:1.5	Eq. (4)
De Jong (1996)	$\frac{H_s}{\Delta D_n}=\left[3.75\left(\frac{N_0}{\sqrt{N}}\right)^{0.5}+0.85f(\varphi)\right]s_{om}^{-0.2}f(R_c/D_n)$	Irregular surging waves; with influence of crest elevation and packing density; slope 1:1.5	Eq. (5)
	$\frac{H_s}{\Delta D_n}=\left[8.6\left(\frac{N_0}{\sqrt{N}}\right)^{0.5}+3.94f(\varphi)\right]s_{om}^{0.2}f(R_c/D_n)$	Irregular plunging waves with influence of crest elevation and packing density; slope 1:1.5	Eq. (6)
Suh and Kang (2012)	$\frac{H_s}{\Delta D_n}=\max\left[\underbrace{\left(9.2\frac{N_0^{0.5}}{N^{0.25}}+3.25\right)\xi_z^{-0.4}}_{\text{I}},\ \underbrace{\left(5\frac{N_0^{0.5}}{N^{0.25}}+0.85\right)(\cot\theta)^{0.45}\xi_z^{0.4}}_{\text{II}}\right]$	I Irregular plunging waves; II Irregular surging waves; randomly placement; slopes:1:1.33–1:2	Eq. (7)

to develop a new stability formula. The new formula demonstrated the applicability of breakwaters with different slope angles.

In most studies, damage of the concrete armor layer is defined as the number of units displaced out of the layer (N_0), i.e. N_0 is the relative damage. Large concrete units can be broken due to the limit of structural strength. In the case where the structural strength plays a role, not only the displaced units but also the rocking and turning units should be taken into account. The number of rocking and turning units or the total number of moving units may provide an indicator of the possible number of broken units. A conservative approach is followed involving the assumption that each moving unit results in a broken unit.

Van der Meer and Heydra (1991) derived the equation to define both moving units and displacing units (see Table 1 and Eq. 3) for tetrapod units.

Another damage ratio formula was proposed by Yagci and Kapdasli (2003). It was used to characterize the damage of the antifer armor layer. The damage ratio is presented as follows:

$$\text{Damage ratio} = \frac{0.25N_\mathrm{R}+0.5N_\mathrm{T}+N_\mathrm{D}}{\text{Total block number}}, \tag{8}$$

where N_R is the number of rocking blocks, N_T is the number of turning blocks, and N_D is the number of displacing blocks. Differing from the classical approach, Eq. (8) also includes both rocking and turning units. This increases the sensitivity of the damage ratio, however, it is difficult to compare their results with previous studies. Yagci and Kapdasli (2003) stated that including the contribution of rocking and turning blocks to the total damage ratio was arbitrarily. They stated that since the main goal of their study was to compare the stability performance of different placement methods under equal condition, the value of coefficients related to rocking and turning blocks in Eq. (8) was not so important. In this study, the damage ratio is shown as $N_{0\mathrm{b}}$.

Three different types of block movements are considered with the assumption of each type contibuting to the damage differently. The descriptions of the movement types are as follows.

Rocking: Blocks move under the effect of the total wave (superposition of incident and reflected waves), but remain at their initial location. The artificial blocks can be broken over time as a result of this movement at their initial location. Therefore, rocking can be considered as a potential source of damage. The contribution of rocking to damage is assumed to be 25%.

Turning: Turning is the movement of a block after leaving its position for a distance shorter than a nominal diameter. In this case, the block after turning may be more or less stable compared with the block in its initial position. If the block is more stable in the new position, it will not move farther. Because the turned blocks have left their initial position, the remaining blocks close to the initial position may be affected. This condition has the potential for damage in the future. The contribution of turning to damage is assumed to be 50%.

Displacing: Displacing is the movement of a block after leaving its initial position for a distance at least a nominal diameter. In this case, the blocks move generally toward the toe and lose their function entirely. The contribution of displacing to damage is assumed to be 100%.

The effect of the tetrapod placement methods on the stability has not been included in previous studies. However, different placement methods of tetrapod blocks result in different hydrodynamic behavior on the breakwater slope. In this study, the stability performance of tetrapod blocks over a 1:1.5 slope under regular and irregular wave conditions is investigated experimentally for two different placement methods of the tetrapod units. The characteristic wave height of irregular waves causing the same damage as regular waves is also determined.

2 Experimental set up

The experiments were performed in a 1 m-wide, 20 m-long and 1 m-high wave flume with glass sidewalls in the Hydraulic and Coastal-Harbor Laboratory of Yıldız Technical University. Fig. 2 shows a schematic layout of the breakwater and the wave gauges in the wave flume. An irregular wave generator was used to generate regular and irregular waves over a horizontal bed at a water depth of 0.60 m. A displacement piston-type wave maker was used to generate waves. It consists of two interconnected shapes rotating relative to each other. The rear surface of each of the components forms the part of a cylinder centered on its axis of rotation. This garantees no back wave formed when the structure rotates. The wave maker measures the incoming wave and corrects the paddle motion to absorb it. The resultant wave ray is totally predictable even with highly re-

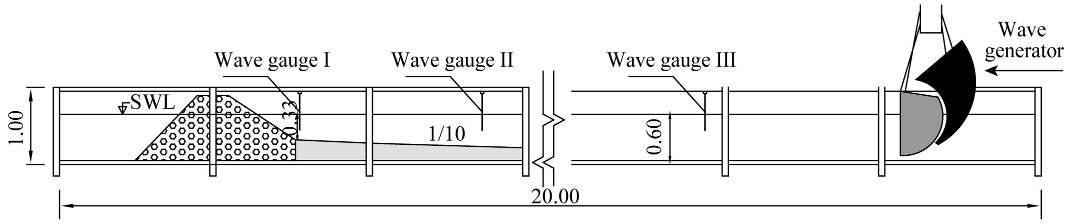


Fig. 2. Wave flume longitudinal cross section (unit: m)

flective models. It can generate both sinusoidal and random waves. HR Wallingford Wave Data software was used for data acquisition and analysis. This software is a spectral analysis program that produces the wave spectrum and associated spectral parameters. It also includes a wave counting routine that uses wave down-crossing to obtain statistical values. A bed with a 1/10 foreshore slope was installed on the flume bottom. The breakwater was located at a water depth of 0.33 m at the other end of the wave flume (Fig. 2).

To measure the waves, three wave gauges were installed in the flume. The first (wave gauge I) was placed at the toe of the breakwater at the water depth of 0.33 m. The second (wave gauge II) was placed at the water depth of 0.53 m on the slope bed. The third (wave gauge III) was located far from the slope bed at the water depth of 0.60 m (Fig. 2). Wave heights measured by Gauge I before the breakwater were taken into account for the stability calculations.

Tetrapods were used for the armor layer of the breakwater. The main characteristics of the tetrapods are: height h=0.07 m, nominal diameter D_n=0.0455 m, mass density ρ_a=2220 kg/m^3, mass M_a=0.189 kg and a layer thickness of 0.094 m. In the filter layer, the stone diameters are in between 0.016–0.032 m with the thickness of 0.05 m. The core consists of stones of the nominal diameter D_{n50}=0.01 m for both placement methods. Breakwaters with armor layers of interlocking units are generally built with steep slopes on the order of 1:1.5 (van der Meer, 1988b). Therefore, such slope angle was chosen for the models. The cross sections are the same except placements for models with two types of armor layer placement method. The cross section of breakwater with Method I is shown in Fig. 3. By using the first and the second placement methods, two layers of tetrapods were placed on the breakwater. Hence, the application of the two placement methods results in different porosities. The porosities are found to be 54% for Method I and 60% for Method II. Consequently, the packing densities are 1.02 and 0.90 for Methods I and II, respectively.

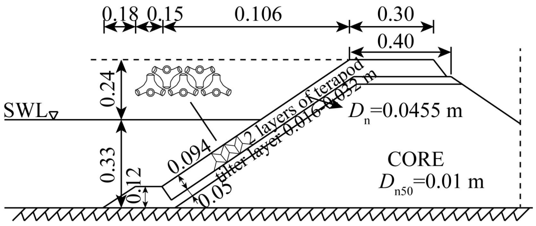


Fig. 3. Cross-section of the model breakwater for Method I (unit: m).

The ranges of wave parameters were measured at the water depth of 0.33 m using wave gauge I and at the water depth of 0.60 m using wave gauge III and presented in Tables 2 and 3 for the regular and irregular wave conditions, respectively. For stability calculations the waves measured by Gauge before the structures are used. All the tests were performed with a fixed cross-section and water depth. The cross-section was completely rebuilt before a new test. In total 158 tests were performed in this study. Seventy-six of these are in regular waves and 82 of these are in irregular waves.

The irregular waves were generated according to the Bretschneider spectrum with each wave ray consisting of approximately 3000 waves. The Bretschneider spectrum used for the experiments is given below

$$S(\omega) = \frac{5}{16}\frac{\omega_m^4}{\omega^5}H_s^2 e^{-5\omega_m^4/(4\omega^4)}, \tag{9}$$

where ω is the frequency in radians per second, ω_m is the modal frequency of any given wave, and H_s is the significant wave height.

Tetrapod block movements under wave attack were visually observed at the side of the flume made from glass during each experiment. At the end of each test the rocking, turning and displacing block numbers were recorded.

The relationship is determined by using dimensional analysis as follows:

$$H_s/(\Delta D_n) = F\left(2\pi H_s/\left(gT_m^2\right),\ N_{0b}, \text{porosity}, \text{slope angle}, \text{wave number}\right), \tag{10}$$

where $H_s/(\Delta D_n)$ is the stability parameter as defined by van der Meer (1988); $2\pi H_s/\left(gT_m^2\right)$ is the wave steepness; T_m is the mean wave period; Δ (=ρ_a/ρ_w−1) is the relative mass density of tetrapods; ρ_a is the mass density of tetrapods; ρ_w is the mass density of water; and N_{0b} is the total relative damage ratio including breakage effect. Hence, the stability number is a function of wave steepness, the damage level, porosity, slope angle and wave number.

Table 2 Range of regular wave parameters

Placements	H_0(m), d=0.60 m	d=0.33 m		s_{om}
		H_d(m)	T_m(s)	
Method I	0.050–0.156	0.035–0.162	0.9–1.5	0.017–0.085
Method II	0.050–0.154	0.052–0.165	0.9–1.5	0.024–0.097

Table 3 Range of irregular wave parameters

Placements	H_{s0}(m), d=0.60 cm	d=0.33 m				s_{om}
		H_s(m)	H_{rms}(m)	$H_{1/10}$(m)	T_m(s)	
Method I	0.048–0.128	0.046–0.121	0.032–0.089	0.058–0.154	0.81–1.38	0.024–0.077
Method II	0.048–0.140	0.045–0.131	0.042–0.091	0.057–0.166	0.81–1.37	0.023–0.077

3 Results and discussion

Experiments were performed in regular and irregular waves with the breakwater slope of 1:1.5. For regular waves, the wave parameters are represented by H_d and T, indicating the wave height and the wave period, respectively, at the toe of the breakwater. The irregular waves can be expressed by different characteristic wave parameters as H_s, H_{rms}, $H_{1/10}$, T_m and T_p. H_s (significant wave height) is the average of the one-third highest wave heights within the wave train, H_{rms} is the root mean square of all the measured wave heights within the wave train, $H_{1/10}$ is the average of the one-tenth highest wave heights within the wave train, T_m is the mean wave period, and T_p is the peak period of the wave spectrum. For the irregular wave tests, the significant wave heights and mean wave periods are chosen to be similar to the regular wave tests.

To evaluate all of the test results in both regular and irregular waves, it is important to determine the wave parameters of irregular waves cause the same damage ratio as those of the regular waves.

Figs. 4a and 4b show the variation of the damage ratio with respect to the wave heights of regular waves (H_d) and irregular waves (H_s, H_{rms}, $H_{1/10}$) with the wave period of T_m=1.35 s for both placement methods. From the figures, it can be observed that the higher wave heights cause the larger damage ratio. It also can be found that the damage ratio caused by $H_{1/10}$ characteristic wave height of irregular waves is comparable to that caused by the wave height of regular wave (H_d). Thus, it can be concluded that $H_{1/10}$ is the characteristic wave height of irregular waves that causes the same damage ratio of regular waves on the stability of tetrapod breakwater armor layer. As the same behavior is observed for the other wave conditions, $H_{1/10}$ is considered as the representative wave height for irregular waves for the rest of the tests.

Some similar studies with different purposes are available in the literatures. The equivalent wave height of regular waves is 1.24 times the significant wave height (H_s) according to the experimental study with irregular and regular waves for a tetrapod rubble-mound breakwater with a slope of 1:1.33 (Fan, 1984). The results of the present study agree well with the results of Fan (1984). In our study $H_{1/10}$ is the best representative parameter of the irregular waves for the stability analysis. It is known that $H_{1/10}$ is equal to $1.27H_s$ according to Rayleigh distribution.

Yu (1985) investigated the influences of the wave length and the wave irregularity on the stability of the armor unit in the regular, irregular and grouping waves. The results reveal that the equivalent wave height of the regular wave is almost equal to $H_{1/10}$ of the irregular wave for rubble-mound breakwater with the slope of 1:1.5. Although the concrete units on armor layer are different from tetrapods in the study, the same result is obtained.

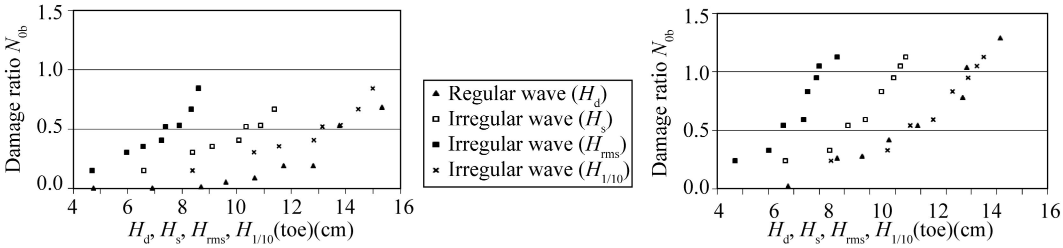
For plunging and surging waves, different stability formulas of amor units were proposed by de Jong (1996) and van der Meer (1988). The critical wave steepness, which determines the transition between plunging and surging waves, can be calculated by Eq. (11). If s_{om} is smaller than s_{omcr}, the waves are surging type. If s_{om} is larger than s_{omcr}, the waves are plunging type.

$$s_{omcr}=\left[\frac{3.75(N_{0b}^{0.5}/N^{0.25})+0.85}{8.6(N_{0b}^{0.5}/N^{0.25})+3.94}\right]^{1/0.4}. \tag{11}$$

The wave steepness range of the test conditions indicates the plunging type wave in the present study. The experimental conditions of the present study were evaluated by using the critical wave steepness (van der Meer, 1999). For plunging waves (Eq. (4)), the stability increases with the increasing wave steepness. The stability increases with the decreasing wave steepness for surging waves (Eq. (2)).

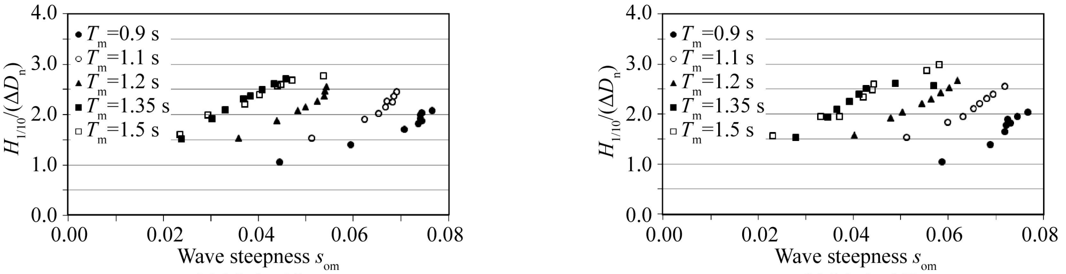
Figs. 5a and 5b show the influence of the wave steepness on the stability with different wave periods for Methods I and II, respectively. As observed from the figures, the stability increases with the increasing wave steepness.

The damage ratios versus stability parameter are drawn for regular and irregular waves for Methods I and II in Figs. 6a and 6b, respectively. The stability parameter is calculated by using H_d for regular waves and $H_{1/10}$ for irregular waves in these figures. It can be seen that H_d and $H_{1/10}$ are compatible from the figures. Yağcı et al. (2004) stated the similar results. Although H_s is obtained as the characteristic wave height for breakwater stability at the beginning of their study by using the determination coefficient, both the stability coefficient and the stability function values obtained from the irregular wave experiments are smaller than those of regular wave series from their experimental study.



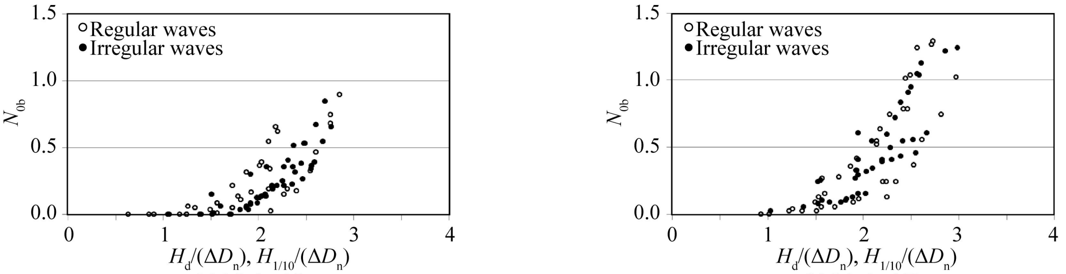
(a) Method I (b) Method II

Fig. 4. Damage versus wave height in regular and irregular waves (T_m=1.35 s).



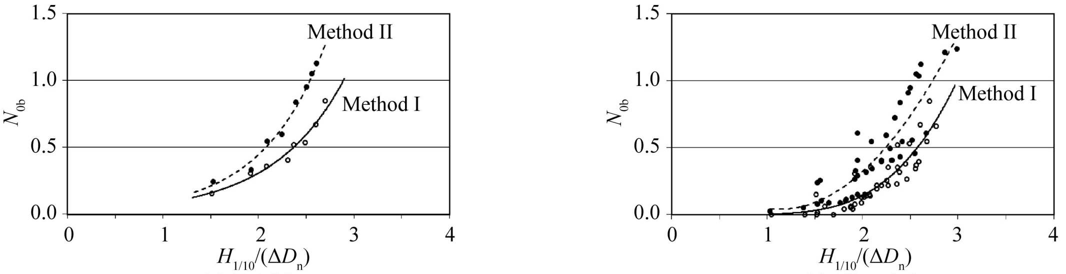
(a) Method I (b) Method II

Fig. 5. Stability parameter $H_{1/10}/(\Delta D_n)$ versus wave steepness.



(a) Method I (b) Method II

Fig. 6. Stability of tetrapods under all wave conditions for regular and irregular waves.



(a) T=1.35 s (b) All periods

Fig. 7. Stability of the tetrapods for Methods I and II.

The wave height of the regular waves is larger than H_s causing the same damage ratio. They concluded that higher damage ratio is observed for irregular waves compared with that of regular waves for the same values of H_s and H_d.

The damage ratio versus the stability parameter $H_{1/10}/(\Delta D_n)$ is plotted for both placement methods with T_m=1.35 s in irregular waves in Fig. 7a. The stability results are also given for all periods in Fig. 7b. It can be observed that the damage ratio for Method II is larger than that for Method I with the same stability. Thus, the placement methods essentially affect the stability of armor units. That the tetrapod blocks placed with Method I is more stable than that with Method II. In the upper layer of Method II, one leg of tetrapod pointing upward leads to the rougher surface than that of Method I. This rougher surface results extra turbulence with more movement and displacement of tetrapods.

The porosities of the armor layer with these two placement methods are different, as well as the packing densities. The porosities of the armor layer for Methods I and II are 54% and 60% with the packing densities of 1.02 and 0.90, respectively. Van den Bosch et al. (2002) and van der Meer (1999) stated that the stability of the armor layer increased with the decrease of the porosity and the increase of the packing density. Therefore, in addition to the rough surface at the armor layer with Method II, the increase of the porosity and decrease of the packing density cause the instability of terapods.

From Fig. 7b, the initial stability parameters $H_{1/10}/(\Delta D_n)$ for Methods I and II are 2.57 and 2.24, respectively, for N_{0b}=0.5 (start of damage). The stability coefficients (K_D) for Methods I and II are about 11.4 and 7.1, showing that the tetrapod blocks palced with Method I is more stable than those with Method II.

Suh and Kang (2012) performed a similar study with two layers of tetrapods. The tetrapods of the upper layer were placed randomly on the regularly placed lower layer. The breakwater slope in their study was 1:1.5. The significant wave heights ranging from 9 to 19 cm were used with T_m=1.36 s. In the present study, the significant wave heights ranging from 6.6 to 11.81 cm are used with T_m=1.35 s. The comparison of the stability parameter varying with wave steepness between the present study and that of Suh and Kang (2012) is shown in Fig. 8. The results of the present study are consistent with the results of Suh and Kang.

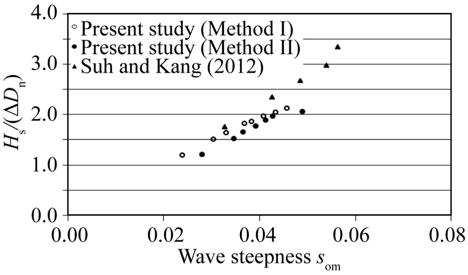


Fig. 8. Comparison of the present study (T_m=1.35 s) with Suh and Kang's (2012) for T_m=1.36 s.

4 Conclusions

The stability of tetrapod blocks in the breakwater armor layer with two placement methods are investigated in the present study. Experiments were conducted with breakwater models in regular and irregular waves. The slope of the modeled breakwater was 1:1.5. The porosities are 54% for Method I and 60% for Method II with the packing densities of 1.02 and 0.90, respectively. The following conclusions are obtained from the test results.

(1) $H_{1/10}$ is found to be the characteristic wave height of the irregular waves causing similar damage ratio to that of regular waves. As the presented results are consistent with previous studies, $H_{1/10}$ wave height is suggested as the design parameter for the stability analysis of tetrapod breakwaters.

(2) The damage of tetrapods placed with Method I is smaller than that with Method II for the same wave heights. The stability parameters $H_{1/10}/(\Delta D_n)$ of tetrapods with Methods I and II are 2.57 and 2.24, respectively for the initial damage N_{0b}=0.5.

(3) Stability coefficients K_D of tetrapods with Methods I and II are about 11.4 and 7.1, respectively.

Therefore, tetrapods placed with Method I are more stable than those with Method II.

Acknowledgements

The authors thank to Prof. Dr. Yalçın Yüksel and Prof. Dr. Esin Çevik. The authors thank the Research Foundation of Yildiz Technical University for their financial support.

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