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피복 방법에 따른 소파블록 피복층의 안정계수에 대한 실험적 연구

Experimental Study of Stability Coefficient of Breakwater Armor Layer Depending on Placement Methods

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Abstract

Experimental Study of Stability Coefficient of Breakwater Armor Layer Depending on Placement Methods

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The rubble mound breakwater is widely used in Korea as well as throughout the world since its construction technology has been developed through extensive experience for a long time. The armor units used to protect the rubble mound breakwater from severe erosion are made of large stones or concrete blocks which are strong and heavy enough so that they are not broken or displaced by the incident waves. For stable and economic design of a breakwater, many studies have been performed for estimating appropriate weight of the armor units. In 1959, Hudson proposed a formula which includes the stability coefficient. The stability coefficients of various armor units including the Tetrapod are given in the Shore Protection Manual published by U.S. Army Corps of Engineers in 1984. However, their applicability is limited because they were developed based on regular wave experiments and only random placement was used for the concrete armor units.

In this study, we propose different placement methods of concrete armor units on a rubble mound breakwater and determine the corresponding stability coefficients. The investigated armor units include the Tetrapod, which is the most widely used in Korea, Rakuna-IV, Dimple, and Grasp-R. The slope of the breakwater is fixed as 1:1.5, which is the most commonly used for rubble mound breakwaters. Regular placement methods are proposed, which are more frequently used in Korea than random placement methods. The stability coefficients are proposed based on the Hudson's formula for different placement methods of each armor unit. Two different placement methods are proposed for Tetrapod and Rakuna-IV, giving similar stability coefficients regardless of the placement method. Dimple is also experimented with two different placement methods whose results show somewhat different stability coefficients. Finally, Grasp-R is experimented with one placement method which results in a larger stability coefficient compared to other armor units.

Keywords: rubble mound breakwater, placement method, Tetrapod, Rakuna-IV, Dimple, Grasp-R, stability coefficient

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Latin Uppercase

B	Flume width
D_n	Nominal size
H	Wave height
H_S	Significant wave height
K_D	Stability coefficient
N	Number of waves
N_d	Number of displaced blocks
N_o	Relative damage
N_S	Stability number
R_c	Crest height
S	Specific gravity
$S(f)$	Wave frequency spectrum
T	Wave period
T_S	Significant wave period
V_w	Fluid velocity

W Weight of breakwater armor

Latin Lowercase

f Frequency

g Gravitational acceleration

h Water depth

l_a Length

Greek Uppercase

Δ $\left(\rho_a/\rho_w - 1\right)$

Greek Lowercase

α Angle of seaside slope

γ_s Specific weight of breakwater armor

θ Slope angle of breakwater

λ Wavelength

μ Kinematic viscosity

ξ_a Roughness length of breakwater armor

ρ_a Density of breakwater armor

ρ_w Density of water

1 Introduction

1.1 Background and necessity of the study

The breakwater is one of the structures in outer harbor that effectively protect a harbor from incident waves. They maintain a harbor tranquility so that ships or vessels may move in and out of harbor safely. They are constructed to minimize the damage from such high waves during a typhoon.

The breakwaters are classified in terms of structural type into the rubble mound breakwater, vertical breakwater, composite breakwater and special breakwater. The rubble mound breakwater is constructed with rubbles and armor units in an inclined mound such that waves are broken to lose their energy on the structure slope (Figure 1.1). Its advantages are possible construction in soft seabed, easier construction and management, and less wave reflection from the breakwater. On the other hand, the usable water area in the harbor is reduced because of large structure width at the bottom and it becomes uneconomical since it requires a large amount of material as the depth increases. The vertical breakwater that consists of massive concrete blocks or caisson is installed almost vertically from the seabed all the way to sea surface. It has to be constructed on a firm seabed (Figure 1.2). It takes up lesser area to be installed compared to the rubble mound breakwater, providing wider usable water area in the harbor and more economical due to smaller cross-sectional area. However, it may cause difficulties in navigation or fishing in neighboring area due to higher reflected waves from the structure. The composite breakwater is a vertical breakwater built on a rubble mound, which has a combined structure of the rubble mound and vertical breakwater (Figure 1.3). The composite breakwater is mostly installed in relatively deep waters since it is easier to construct on an irregular seabed and it is more economical than the rubble mound breakwater due to the vertical structure of the main body. There also are special breakwaters such as pneumatic breakwater, floating breakwater and submerged breakwater.

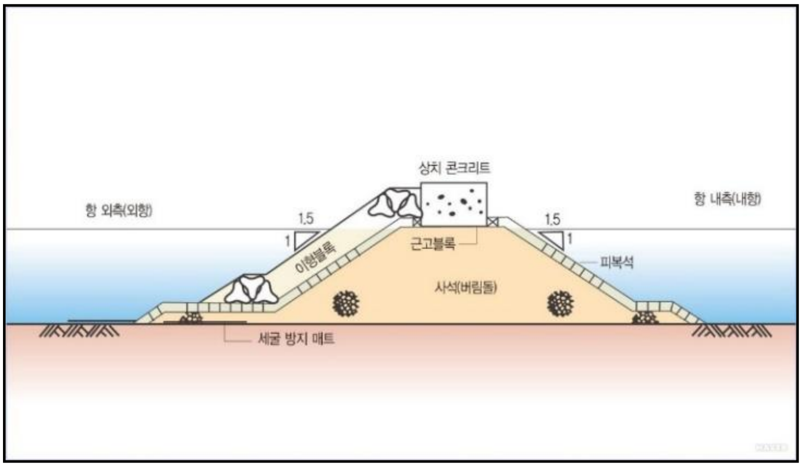


Figure 1.1 Rubble mound breakwater

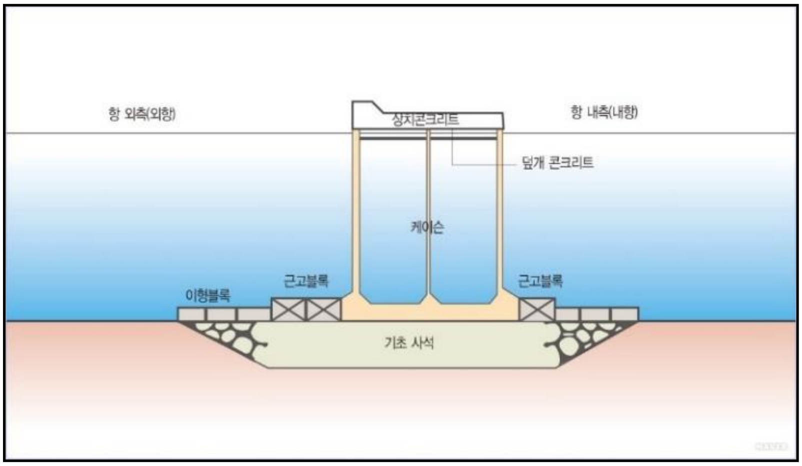


Figure 1.2 Vertical breakwater

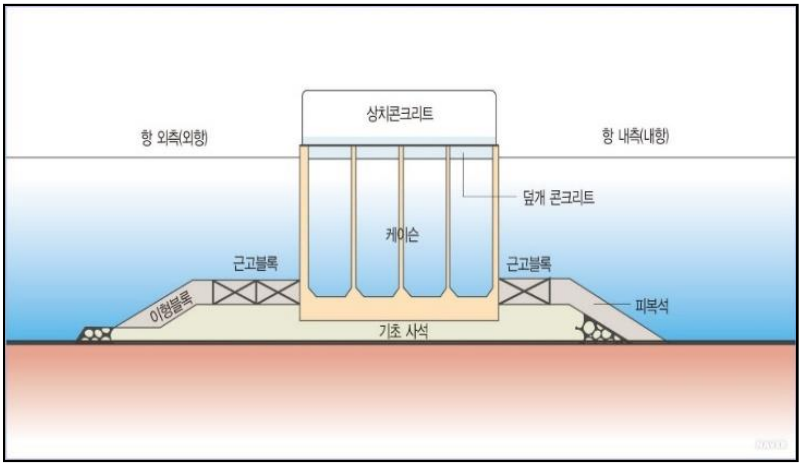


Figure 1.3 Composite breakwater

Among the breakwaters mentioned above, construction technology of the rubble mound breakwater has been advanced by long-time experiences and is the most widely used in Korea as well as around the world. The armor units used in the rubble mound breakwater is mostly made of large stones or concrete blocks that are strong and heavy enough against severe incoming waves. Today's widely used armor units include Tetrapod, Cube, Dolos, Tribar, Accropode, Tripod, Core-Loc, Dimple, Grasp-R, and Grasp-P. Especially, Tetrapod is the most widely used in Korea (Figure 1.4).

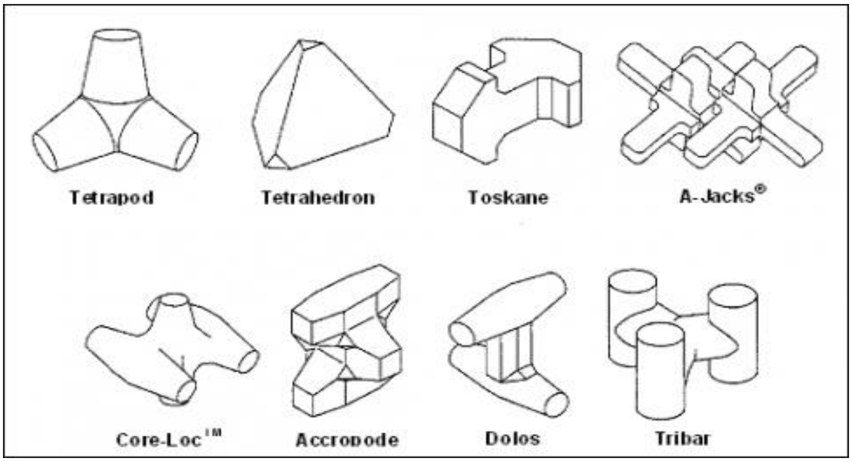


Figure 1.4 Concrete armors (Lagasse et al., 1997)

Since the breakwater armor units should be heavy enough to withstand the high waves during the peak of a storm, there have been numerous studies to develop various types of armor units. The Tetrapod which is the most widely used in Korea is the oldest concrete armor unit, and many researches have been conducted to compute the appropriate weight of Tetrapod (De Jong (1996); Hanzawa et al. (1996); Hudson (1959); Van der Meer (1988) etc.). The Hudson (1959) formula has been the most frequently used in designing the breakwater armor units in Korea, which includes the stability coefficient (K_D) for estimating the appropriate weight of Tetrapod as well as other breakwater armor units. Stability coefficients for different armor units are presented in the Shore Protection Manual (SPM) published by the U.S Army Corps of Engineers (1984). However, their applicability is limited because they were developed based on regular wave experiments and only random placement was used for the concrete armor units. Especially in the case of Tetrapod, the SPM presented the stability coefficient for the random placement method. However, it is not readily feasible in Korea where the regular placement method is widely used.

In an effort to develop a more stable armor unit in similar form to Tetrapod, Nikken Kogaku Co., Ltd. of Japan developed the Rakuna-IV. Suh et al. (2013) presented a stability formula to be used in broad range of conditions, but there has been no study of the stability coefficient for Rakuna-IV.

In this study, we carry out experiments to present stability coefficients for Tetrapod and Rakuna-IV so that they can be used in the design of rubble mound breakwaters in Korea. Especially in the case of Tetrapod, the regular placement method is proposed, which has not been considered in the SPM, so it can be used in Korean harbors. In addition, studies of stability coefficients for Dimple and Grasp-R are also carried out.

1.2 Literature review and research objectives

The SPM presents the stability coefficients for Tetrapod using the Hudson (1959) formula as shown in Table 1.1. The stability coefficient in the SPM corresponds to the initial damage of 0~5 %, presenting 7.0 for breaking wave condition and 8.0 for non-breaking wave condition where Tetrapods are randomly placed in two layers. However, it is not reasonable to use the SPM's stability coefficient since the regular placement method is more widely used in Korea than the random placement method.

Table 1.1 Suggested K_D-values of Tetrapod in Shore Protection Manual (U.S Army Corps of Engineers, 1984)

Armor Units	Placement	Structure Trunk	
		Breaking Wave	Non-breaking Wave
Tetrapod	Random	7.0	8.0

There have been several studies for investigating the stability of Tetrapod for regular placement methods. Gürer et al. (2005) made experiments for two different placement methods for two layers of Tetrapod (Figure 1.5). They investigated the stability of Tetrapod depending on placement methods by performing experiments for 181 conditions using the significant wave heights between 0.03 and 0.21 m and four different significant wave periods (1.10, 1.35, 1.50 and 1.80 s) for non-breaking waves impinging onto 1:1.5 slope breakwater in water depth of 0.6 m. Observing the relative damage against the incident wave height with the use of the stability coefficient of 8.0, they showed that the placement method shown in Figure 1.5b had better initial stability than the method in Figure 1.5a. Figure 1.6 shows a comparison of stability coefficient against wave steepness. However, verification or application in hydraulic experiment or real field poses a challenge since Gürer et al. (2005) did not explain the placement methods in detail.

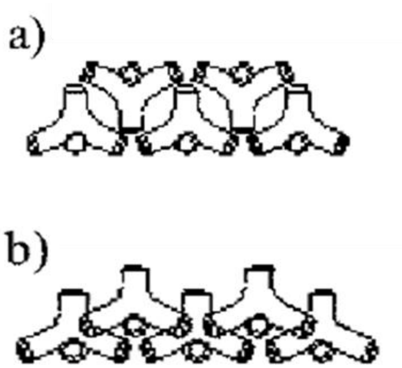


Figure 1.5 A scheme for different placing methods (Gürer et al., 2005)

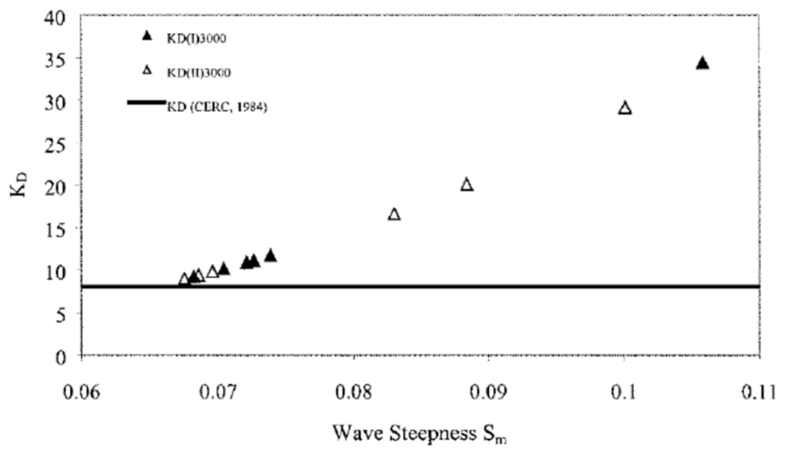


Figure 1.6 Comparison of the stability with SPM (1984) (Gürer et al., 2005)

Fabião et al. (2013) performed the stability experiments of Tetrapod for the two regular placement methods shown in Figure 1.7. Tetrapods of 192.5-g average weight (W), 6.4-cm height (h), 2617-kg/m^3 density (ρ_a), and 4.2-cm nominal size (D_n) were placed on a 1:1.5 rubble mound breakwater, and experiments were performed with 0.12 ~ 0.18 m significant wave height (H_s) with a fixed wave period (T) of 1.40 s. The result showed that the placement method in Figure 1.7A showed better stability than that in Figure 1.7B (see Figure 1.8). However, the placement methods used in their experiment are not realistically applicable.

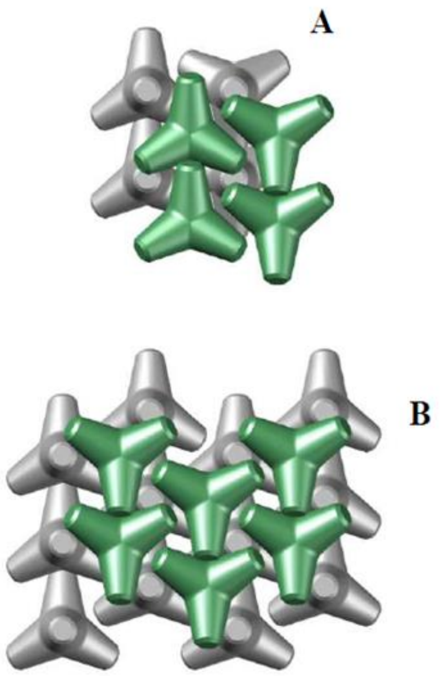


Figure 1.7 A scheme for different placing methods (Fabião et al., 2013)

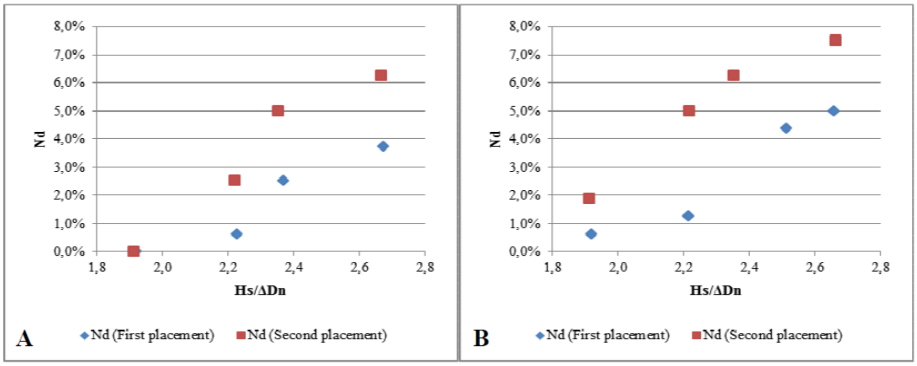


Figure 1.8 Damage progress for N = 1000(A) and N = 3000(B)

(Fabião et al., 2013)

For the Rakuna-IV developed by Nikken Kogaku Co., Ltd., Suh et al. (2013) presented a stability formula by analyzing the experimental data for various structure slopes and wave conditions including both surging and plunging breakers, but they did not perform the experiment for determining the stability coefficient.

On the other hand, no study has been performed of the stability coefficients for Dimple and Grasp-R as well as the armor units mentioned above.

The objectives of the present study are to propose more easy-to-construct regular placement methods for Tetrapod, Rakuna-IV, Dimple, and Grasp-R and to estimate the stability coefficient for each method by performing hydraulic experiments.

2 Theoretical background

2.1 Hydraulic experiment with breakwater

The natural phenomenon can be studied either by field observations just as it is; by numerical simulations using computers and numerical modeling techniques; or by hydraulic experiments with reproduction of scaled natural phenomenon in a laboratory without assumptions or simplifications. In the case of a breakwater, hydraulic experiments are frequently used rather than field observations that require a lot of equipment, manpower, money and time or numerical simulations that are not capable of accurately simulating complex hydraulic phenomena. In hydraulic experiments of breakwaters, results are more accurate with a model closely resembling the prototype. However, due to constraints of cost and space, a model with an appropriate scale is used to provide reliable results.

2.1.1 Similitude

When a theoretical analysis is not easy, mechanical properties of a prototype can be predicted using a model manufactured by reducing the prototype. Similitude of flow phenomena occurs between a prototype and its model. There are three types of similitude; geometric similitude which states that the model and prototype have the similar shape, kinematic similitude which requires that the ratios of velocities and accelerations must be the same between the model and prototype, and dynamic similitude which means that the forces acting on corresponding fluid masses must be related by ratios similar to those for kinematic similitude. In most engineering problems, only several forces are important depending on the problem. In hydraulic experiments of the breakwater armor, the important forces are the inertia force and gravity force, the ratio of which is represented by the Froude number given by Eq. (2.1). The hydraulic experiment, therefore, is performed so as to satisfy the Froude similitude which requires that the Froude numbers are the same between model and prototype.

$$Fr = \frac{U}{\sqrt{gl}} \tag{2.1}$$

where U is fluid velocity, g is gravitational acceleration, and l is length. In the application of the Froude similitude, it is known that the influence of surface tension or air content in water is not significant when the water depth is greater than 2 ~ 3 cm and the wave period is greater than 0.3 s (Sveinbjörnsson 2008).

2.1.2 Dimensional analysis

Similitude is a means of correlating the apparently divergent results obtained from similar fluid phenomena and as such becomes a valuable tool of modern fluid mechanics. It enables one to use the results obtained in a laboratory test for the investigation of actual phenomena or design of prototype structures. In studying the actual phenomenon with a scaled model, the relationships between the prototype and model have to be established. There are numerous variables related to the stability of the armor units of rubble mound breakwaters. Hudson et al. (1979) considered the stability formula for the rubble mound breakwater as a function of relevant variables.

Assuming that the stability formula is a function of relevant variables, the functional relationship among the variables can be written in the form

$$f\left(V_w, g, \rho_a, \rho_w, \mu, H, \lambda, h, l_a, \xi_a, \alpha, \theta\right)=0 \tag{2.2}$$

where V_w is fluid velocity around the breakwater armors, g is gravitational acceleration, ρ_a is density of breakwater armor, ρ_w is density of water, μ is viscosity of water, H is wave height, λ is wavelength, h is water depth in front of the breakwater, l_a is length of breakwater armor, ξ_a is roughness length of breakwater armor, α is slope angle of seabed, and θ is slope angle of structure. Even though the wave period which is an important factor in the experiment is not included in the equation, it is indirectly included by the relationship between wave period and wavelength. Among the variables in Eq. (2.2), V_w, H, λ, h, α, and g are related to the wave force, whereas

ρ_a, ρ_w, l_a are related to the buoyancy of the breakwater armor. On the other hand, μ and ξ_a are related to viscosity and frictional force, and θ is related to the structure. Hudson et al. (1979) re-expressed Eq. (2.2) as a function of dimensionless variables as shown below.

$$f'\left(\frac{V_w}{\sqrt{gl_a}},\frac{V_w l_a}{\mu/\rho_w},\frac{\rho_w}{(\rho_a-\rho_w)},\frac{l_a}{h},\frac{H}{\lambda},\frac{h}{\lambda},\frac{\xi_a}{l_a},\alpha,\theta\right)=0 \tag{2.3}$$

The above function suggests the similitudes between model and prototype as follows.

$$\left(\frac{V_w}{\sqrt{gl_a}}\right)_p=\left(\frac{V_w}{\sqrt{gl_a}}\right)_m \tag{2.4}$$

$$\left(\frac{V_w l_a}{\mu/\rho_w}\right)_p=\left(\frac{V_w l_a}{\mu/\rho_w}\right)_m \tag{2.5}$$

$$\left(\frac{\rho_w}{\rho_a-\rho_w}\right)_p=\left(\frac{\rho_w}{\rho_a-\rho_w}\right)_m \tag{2.6}$$

$$\left(\frac{l_a}{h}\right)_p=\left(\frac{l_a}{h}\right)_m \tag{2.7}$$

$$\left(\frac{H}{\lambda}\right)_p=\left(\frac{H}{\lambda}\right)_m \tag{2.8}$$

$$\left(\frac{h}{\lambda}\right)_p=\left(\frac{h}{\lambda}\right)_m \tag{2.9}$$

$$\left(\frac{\xi_a}{l_a}\right)_p = \left(\frac{\xi_a}{l_a}\right)_m \tag{2.10}$$

$$(\alpha)_p = (\alpha)_m \tag{2.11}$$

$$(\theta)_p = (\theta)_m \tag{2.12}$$

where the subscripts p and m denote prototype and model, respectively. Eqs. (2.4) and (2.5) represent the Froude similitude and Reynolds similitude, respectively. The gravity force, inertia force, and viscous force are important forces. If the experiment is carried out so as to satisfy the Froude similitude that relates the gravity force to inertia force, the Reynolds similitude relating the viscous force to inertia force is automatically satisfied.

2.2 Damage of armor units

2.2.1 Definition of damage

The SPM defines the damage as the percent damage given by Eq. (2.13), which is the percentage of the number of displaced armor units against the total number of armor units in the active zone where most damage occurs by the waves. The active zone is usually defined as the area of $\pm H_s$ from the still water level, since most damage occurs in this area.

$$\text{Damage}(\%) = \frac{\text{Number of displaced units}}{\text{Number of units within active zone}} \times 100 \tag{2.13}$$

Van der Meer (1988) proposed to use the relative damage (N_0) given by Eq. (2.14) instead of the percent damage of the SPM. The relative damage is defined as the number of displaced armor units in the width of nominal size of the unit along the crest line of the breakwater.

$$N_0 = \frac{N_d}{B / D_n} \tag{2.14}$$

where N_d is the number of displaced armor units, B is the width of the wave flume, and D_n is the nominal size which is defined as the side length of a cube which has the same volume as the armor unit.

The stability coefficient in the Hudson formula is calculated with the wave height that produces the percent damage of 5% (initial damage). However, the experimental condition is a laboratory has much less uncertainty compared with the field condition. Therefore, the initial damage is assumed when a single armor unit is displaced (in other words, the percent damage is greater than 0 %). The wave height for the initial damage is then used to calculate the stability coefficient. The armor units in contact with the wall of the flume are not counted because they have less interlocking with neighboring units.

2.2.2 Measurement of damage

The damage of breakwater armor units in the field occurs in the form of displacement, sliding, or breakage due to repeating large waves generated during a storm. In the hydraulic experiments, however, the armor units can be displaced or slid but rarely broken, because the size of the armor unit is reduced following the Froude similitude but its strength remains the same. Therefore, there is a possibility of the damage to be underestimated in the hydraulic experiment. To compensate this underestimation, in the present experiment, the following behaviors of armor units are considered to be a damage.

① When the armor unit is completely displaced from its original position.

② When the armor unit has been displace and returns to its original position: the armor unit is raised up by an incoming wave and then falls down into its original position, or a displaced armor unit returns to its original position by the subsequent incoming wave.

③ When the armor unit is slid out of its original position for more than one nominal size of the armor unit.

④ When the armor unit rotates more than 180° on its position.

The damage was observed visually and by using a camcorder in this experiment.

2.3 Stability coefficient (K_D)

2.3.1 Hudson (1959) formula

Hudson (1959) proposed a formula for calculating the weight of a breakwater armor unit considering the inertia force which was considered in the study of Iribarren and Nogales (1950) because of insufficient accuracy. He proposed the following formula by including the effects of the variables other than wave height, structure slope, and the specific gravity of the armor units in the stability coefficient.

$$W = \frac{\rho_a H^3}{N_s^3 \left(\frac{\rho_a}{\rho_w} - 1 \right)^3} \tag{2.15}$$

$$K_D = \frac{\gamma_s H^3}{W (S-1)^3 \cot\theta} \tag{2.16}$$

where W is weight of the armor unit, N_s is stability number, γ_s is specific weight of the armor unit, S is specific gravity of the armor unit, and θ is slope angle of the breakwater. Hudson (1959) formula is simple but applicable in a variety of breakwater armors, so it is widely used in Korea.

3 Hydraulic Experiment

3.1 Outline

Hydraulic experiments were conducted to analyze the stability of the Tetrapod, Rakuna-IV, Dimple, and Grasp-R armoring a rubble mound breakwater, and to estimate their stability coefficients (K_D). The experiments were conducted in the wave flume in the hydraulic and coastal engineering laboratory of Seoul National University with 1:50 scale. The model armor units were manufactured by Hyosung Industry in Korea and Nikken Kogaku Co., Ltd. in Japan. Wave measurements were made using three wave gauges at 20 Hz sampling intervals, and all experiments were recorded by a camcorder. Damages to the armor units were visually observed with a help from recorded image when the determination of damage was not clear.

3.2 Experimental devices

Facilities in the hydraulic and coastal engineering laboratory of Seoul National University include the wave flume, wave maker, wave gauges and a computer that controls these facilities and collects data.

3.2.1 Wave flume

Specification of the wave flume is shown in Figure 3. 1 and Figure 3. 2. It was 36-m long, 1.0-m wide and 1.2-m high, and wave absorbers were installed at both ends to reduce wave reflection. A piston type wave maker was installed at one end of the wave flume. From the point 20 m away from the wave maker, a plane slope was installed for 5 m up to the elevation of 0.2 m to simulate a foreshore slope of 1:25. From the point 12 m away from the wave maker, the wave flume was divided into two channels of 0.6 m and 0.4 m widths. The experimental structure was installed in the 0.6-m channel, whereas wave gauges were installed in the 0.4-m channel to measure the waves without the influence of wave reflection from the structure. A side wall of the wave flume is made of transparent reinforced glass for visual observation of the experiment.

Figure 3.1 Photograph of wave flume

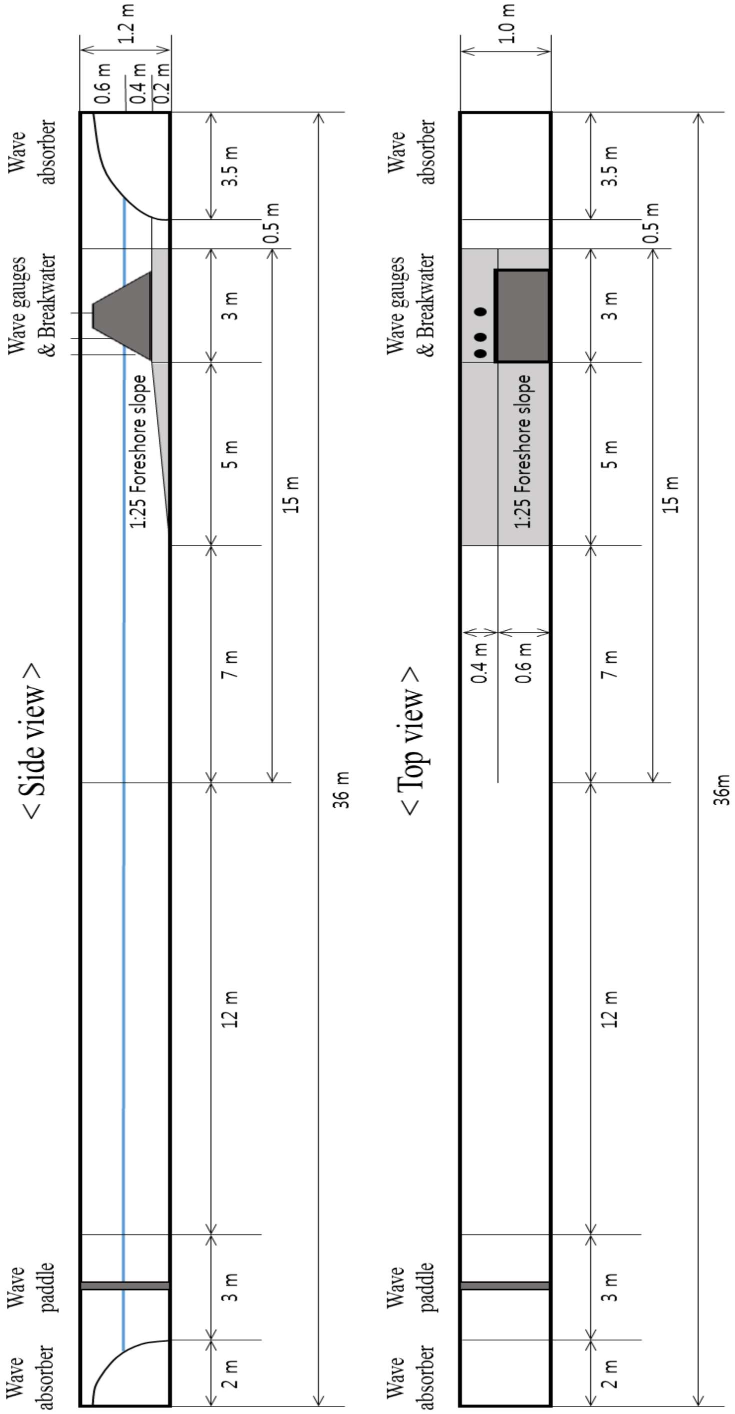


Figure 3.2 Sketch of wave flume and experimental setup

3.2.2 Wave maker and controlling device

The wave maker is a two-dimensional piston type that is able to generate irregular waves of several types of wave spectra as well as regular waves through a computer-controlled wave generating program. The wave spectra that can be generated include Bretschneider-Mitsuyasu spectrum, Modified Bretschneider-Mitsuyasu spectrum (same as Pierson-Moskowitz spectrum), and JONSWAP spectrum. The computer converts the wave signal of a spectrum into the wave paddle signal and transmits it to the control panel, which then transmits the signal to the servo motor to move the wave paddle. Waves generated by the wave paddle are measured by wave gauges to obtain the wave data. The specification of the wave maker is given in Table 3.1.

Table 3.1 Specification of wave maker

Item	Specification
Wave paddle	1.0 (W) × 1.2 (H) m
Max. wave height	0.6 m (in front of wave maker)
Wave period	0.3 ~ 5.0 s
Wave generator	AC servo motor
Wavemaker control	Reflected wave absorbing control using PC
Panels	Control panel & Operation panel
Wavemaker type	Piston type
Types of wave	Regular and irregular waves
Power	AC 220V, 60 Hz (Control panel) AC 110V, 60 Hz (Operation panel)

3.2.3 Wave gauge

The wave gauge used in this experiment is a capacitance type wave gauge that consists of two parallel insulated wires, which measure the change of electrical capacitance between the wires and water surface by using the condenser formed between the conductor and water and computes the change in surface elevation. The wave gauge is the model WHG40 manufactured by Sewon Engineering Co., which is excellent in linearity and responsibility. Its detection line is 0.8 m long, and the wave height measurement range is ± 0.4 m.

3.3 Model manufacturing and installation

3.3.1 Model manufacturing

A rubble mound breakwater was used in this experiment which had a slope of $\cot\theta = 1.5$, the most frequently used slope in Korea. The breakwater consists of a core consisted of stones of nominal size smaller than 1.5 cm, and the filter layer and toe consisted of stones of nominal size 1.6~1.8 cm and average weight of approximately 13.5 g (see Figure 3.7). The Tetrapod used in the experiment was 32 ton class in the prototype, and it was 7.1 cm high (h), 4.64 cm of nominal size (D_n), 2.23 g/cm^3 of density (ρ_a), and the saturated weight(W) was approximately 223.5 g with the scale of 1:50 (see Figure 3.3). The Rakuna-IV was 16 ton class in the prototype, and it was 3.80 cm of nominal size (D_n) and 127.1 g of saturated weight (W) in the laboratory (see Figure 3.4). For Dimple of 20 ton class, the nominal size (D_n) was 4.10 cm and the saturated weight (W) was 151.0 g (see Figure 3.5). The Grasp-R was 16 ton class with the nominal size (D_n) and saturated weight (W) of 3.82 cm and 128.1 g, respectively (see Figure 3.6).

Figure 3.3 A photograph of Tetrapod

Figure 3.4 A photograph of Rakuna-IV

Figure 3.5 A photograph of Dimple

Figure 3.6 A photograph of Grasp-R

Table 3.2 Size and weight of model armor units and stones

		Size and weight	
		D_n or D_{50} (cm)	W or W_{50} (g)
Armor units	Tetrapod	4.64	223.5
	Rakuna-IV	3.80	127.1
	Dimple	4.10	151.0
	Grasp-R	3.82	128.1
Graded stones	Filter layer, Toe	1.6 ~ 1.8	13.5
	Core	0.5 ~ 1.5	1.03

The 1:25 plane slope from the channel bottom to the location of the structure was manufactured from stainless steel. The water depth was constant as 0.6 m in front of the wave maker and 0.4 m in front of the breakwater. The crest height (R_c), the vertical distance from the still water level (SWL) to the top of the breakwater, was 0.34 m, so that the total height of the breakwater was 0.74 m.

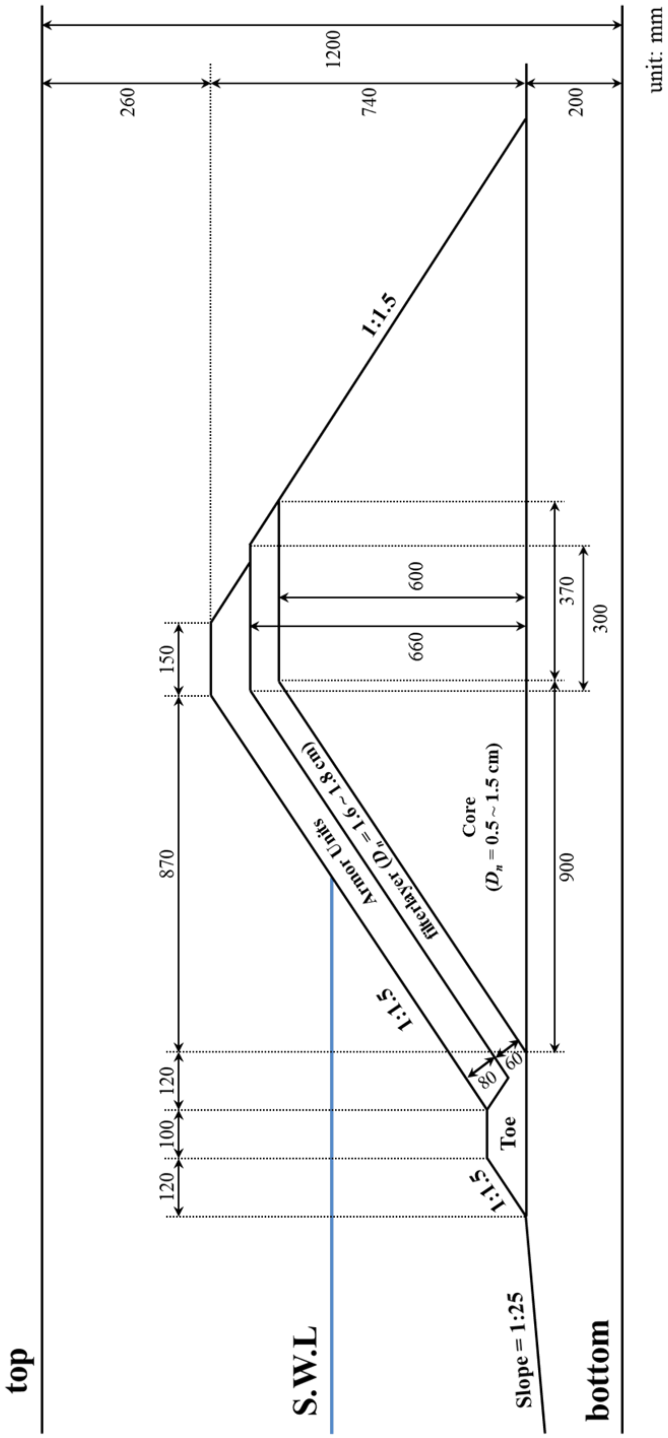


Figure 3.7 A cross-section of breakwater ($\cot\theta = 1.5$)

3.3.2 Model installation

For 15 m starting at 13 m away from the wave maker, the wave flume was divided into two channels, one 0.6 m wide and the other 0.4 m wide. The breakwater was installed in the wider channel of the two and the wave gauges were installed in the other channel. In the width of 0.6 m of the breakwater, approximately 9 Tetrapods, 11 Rakuna-IV's, 8 Dimples and 9 Grasp-R's could be installed. The armor units abutting side walls had less interlocking effects, so these armor units were fixed firmly and were not included in the area of damage. The armor units were placed in two layers in the vertical direction. They were painted in different colors for each two rows for easier visual observation of damage (see Figure 3.8). The breakwater was installed at the location which is 25 m away from the wave maker and where the 1:25 plane slope ends.

Three wave gauges were installed to separate the incident and reflected waves using the 3-point separation technique (Suh et al., 2001). In order to separate the incident and reflected waves, the distance between the wave gauges should be within one wavelength. Accordingly, the distance between the first and second wave gauges was 0.3 m and the distance was 0.5 m between the second and third gauges. To measure the incident wave profile at the location of the breakwater, the wave gauges were installed in the narrower channel but at the same location as the breakwater.

Figure 3.8 A photograph of breakwater

3.4 Test cases and procedure

3.4.1 Wave conditions

The scale of the experiment was 1:50 and the significant wave height and period were computed by the Froude similitude. The significant wave period (T_s) was 13 s in the prototype so that it was 1.84 s in the experiment. The significant wave height (H_s) was 5.6 ~ 8.4 m in the prototype, being 11.2 ~ 16.8 cm in the experiment. The range of significant wave height was different depending on the armor unit (see Table 3.3).

Table 3.3 Wave conditions

Armor unit	Case	Prototype		Model	
		T_s (s)	H_s (m)	T_s (s)	H_s (cm)
Tetrapod	1	13	6.0	1.84	12.0
	2		6.2		12.4
	3		6.4		12.8
	4		6.6		13.2
Rakuna-IV	1	13	5.6	1.84	11.2
	2		5.8		11.6
	3		6.0		12.0
	4		6.2		12.4
Dimple	1	13	7.4	1.84	14.8
	2		7.6		15.2
	3		7.8		15.6
	4		8.0		16.0
	5		8.2		16.4
	6		8.4		16.8
Grasp-R	1	13	6.0	1.84	12.0
	2		6.2		12.4
	3		6.4		12.8
	4		6.6		13.2

3.4.2 Spectrum amendment

The wave spectra that can be generated by the wave maker in the hydraulic and coastal engineering laboratory of Seoul National University include the Bretschneider-Mitsuyasu spectrum, modified Bretschneider-Mitsuyasu spectrum, and JONSWAP spectrum. The modified Bretschneider-Mitsuyasu spectrum given by Eq. (2.17) was used in this experiment, which is identical to the Pierson-Moskowitz spectrum.

$$S(f) = 0.205 H_s^2 T_s^{-4} f^{-5} \exp\left[-0.75 (T_s f)^{-4}\right] \tag{2.17}$$

where $S(f)$ is the wave spectral density function, f is frequency, H_s is significant wave height, and T_s is the significant wave period.

Since it was not possible to completely simulate the real waves in the laboratory, 100 regular waves with different periods were superimposed to generate irregular waves. However, the spectrum of such generated waves shows a difference from the target spectrum. In order to reduce the difference, the spectrum amendment was made until the measured spectrum became very close to the target spectrum. The spectrum amendment was carried out for each wave condition, and the finally amended spectrum was used in the main experiment for armor stability.

Figure 3.9 shows an example of the target spectrum and the estimated spectrum using 500 waves prior to the installation of the breakwater.

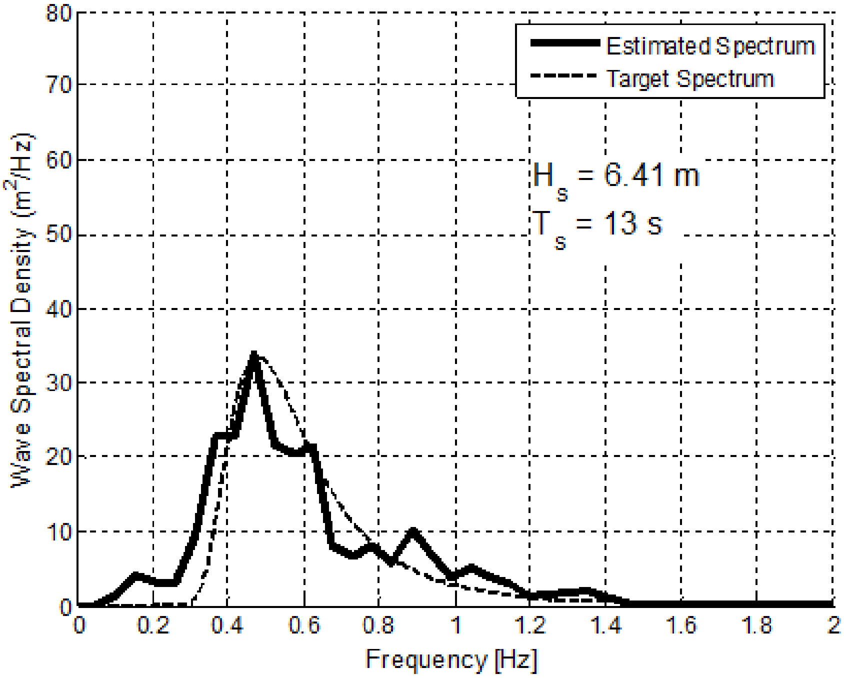


Figure 3.9 Example of spectrum amendment

3.4.3 Experimental procedure

The experiments were performed according to the procedure as follows:

① The core, filter layer and toe of the breakwater of 1:1.5 slope were installed in an empty wave flume.

② Fill the wave flume with water until the depth is 0.6 m.

③ Place the armor units.

④ Install the wave gauges and calibrate them.

⑤ Generate small waves of $T_s = 1.83$ s and $H_s = 0.11$ m for approximately 500 seconds to stabilize the breakwater and armor units.

⑥ Generate waves using the amended spectrum.

⑦ Acquire the wave data from the time when a steady wave field was established in the wave flume (approximately 100 s after the initiation of wave generation).

⑧ Observe the damage of armor units by generating 500 waves. If there is no damage, generate the next 500 waves with the height increased by 0.2 m (in prototype).

⑨ Repeat the increase of wave height by 0.2 m until damage is observed.

⑩ Stop the experiment when damage is observed and separate the incident and reflected waves using the 3-point separation technique (Suh et al., 2001) with the acquired wave data.

⑪ Compute the significant wave height and period using the zero-crossing method.

⑫ Generate the next 500 waves that is higher by 0.2 m than the waves that first created damage to confirm whether damage increases.

⑬ Compute the stability coefficient using the Hudson (1959) formula.

⑭ Remove all the armor units and place them again, and repeat five times the same experiment.

3.4.4 Effect of different weight class of armor units

The weight classes of the armor units used in this study are 32 ton for Tetrapod, 16 ton for Rakuna-IV and Grasp-R, and 20 ton for Dimple. One may wonder if the difference in weight classes of armor units affects the experimental results. To resolve this question, tests were performed with two different weights of Tetrapods as shown in Figure 3.10. The same wave period was used in both tests, but different wave heights were used because the weights of Tetrapods were different. The test results are given in Table 3.4. For the weights of 16 ton and 32 ton, the damage started at the wave heights of 5.6 m and 6.46 m, respectively. However, the corresponding stability coefficients are 7.43 and 7.50, which are close each other. Therefore, we could conclude that the use of the armor units of different weight classes does not affect the experimental results.

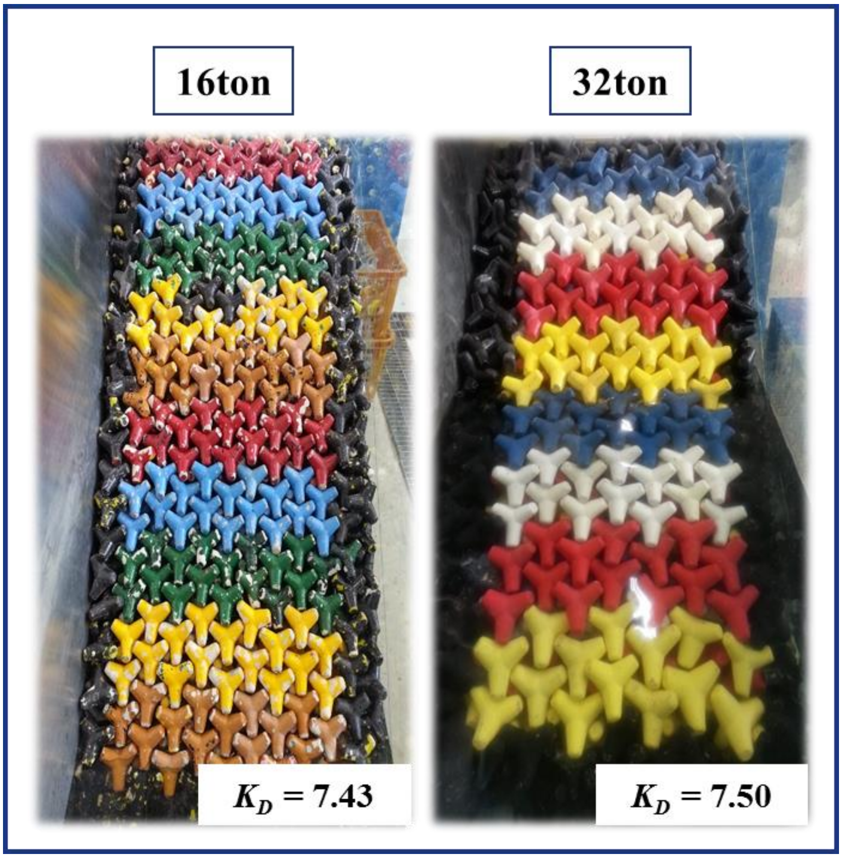


Figure 3.10 Breakwater slopes armored with Tetrapods of different weights

Table 3.4 Stability coefficients for different weight classes of Tetrapod

Weight	16 ton	32 ton
H_s	5.6 m	6.46 m
Stability coefficient	7.43	7.50

4 Results and Analysis

4.1 Tetrapod

As seen in Figure 4.1 and Figure 4.2, Tetrapods were placed in two different methods and tested under the same condition (Table 4.1). The tests were repeated five times to compute the average stability coefficient. In the Method 1, damage started to occur at the wave height of 6.46 m which gives the stability coefficient of 7.50. In the Method 2, damage started to occur at the wave height of 6.40 m which gives the stability coefficient of 7.28. Therefore, the Method 1 is slightly more stable than the Method 2. More detailed experimental results including average, standard deviation, and coefficient of variation of stability coefficient are given in Table 4.2.

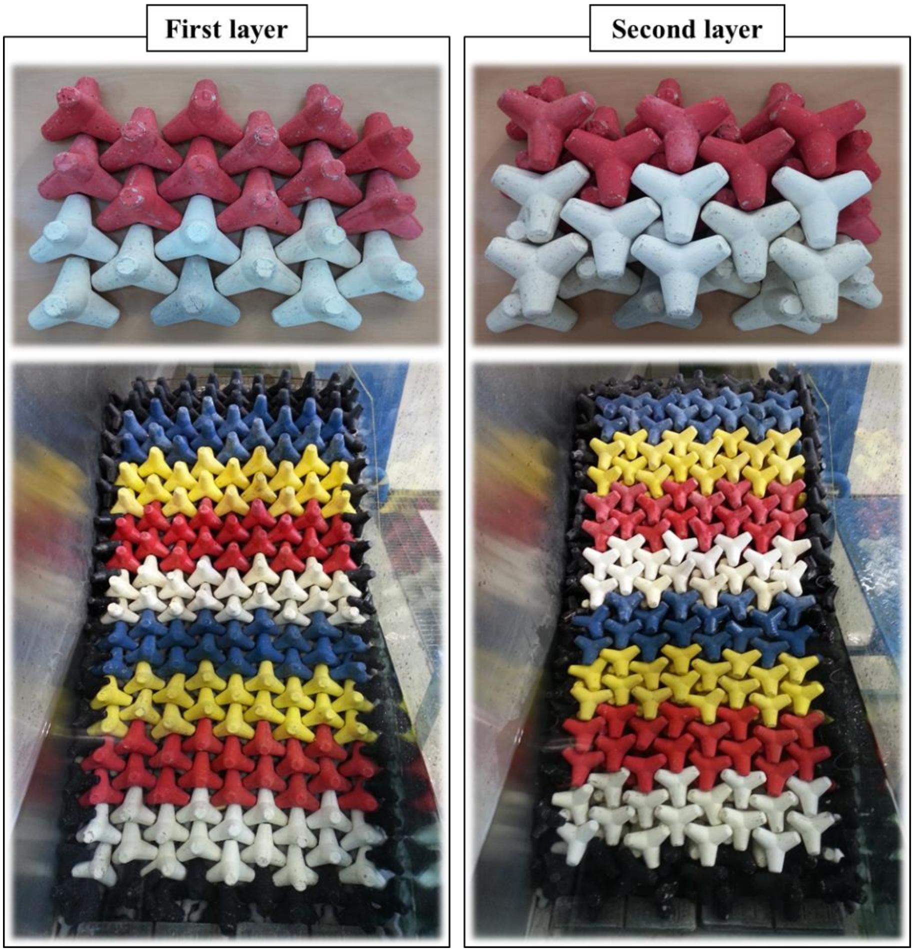


Figure 4.1 Placement method 1 of Tetrapod (Porosity: 54 %)

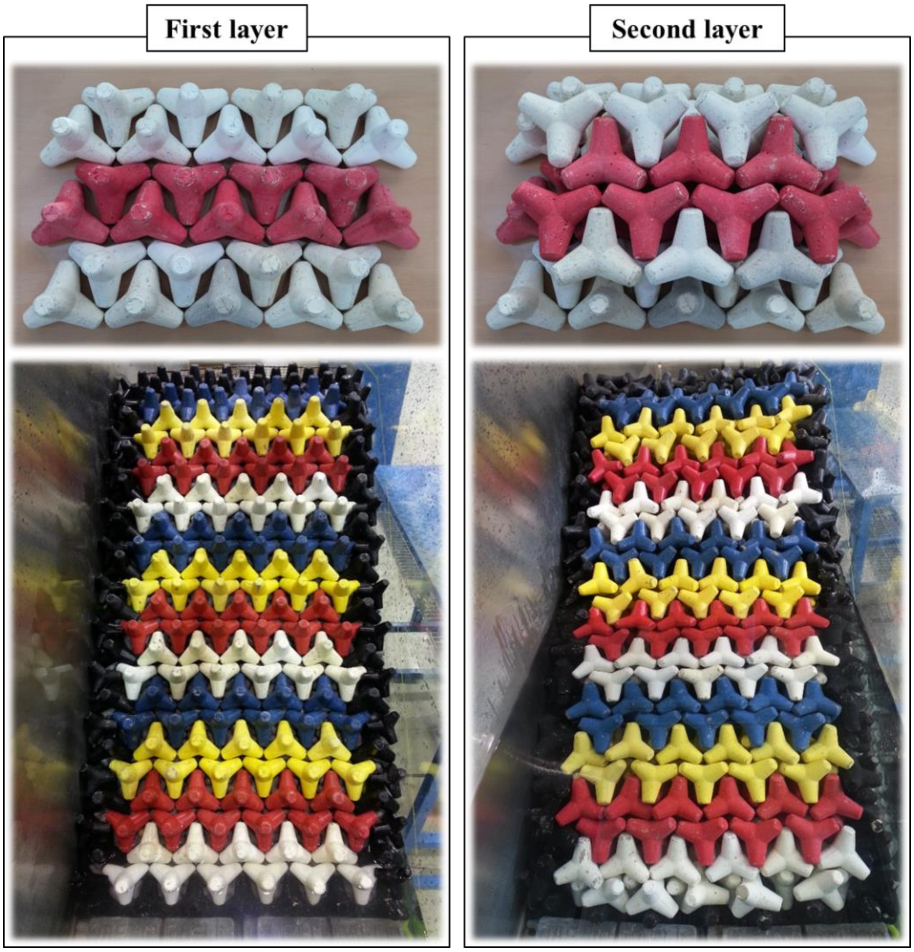


Figure 4.2 Placement method 2 of Tetrapod (Porosity: 54 %)

Table 4.1 Wave conditions of Tetrapod (scale 1:50)

	Field	Experiment
T_s	13 s	1.84 s
H_s	5.8 m ~ 6.8 m	11.6 cm ~ 13.6 cm
Weight	32 ton class (28.75 ton)	223.5 g

Table 4.2 Comparison of stability coefficients (K_D) between two different placement methods of Tetrapod

	Method 1		**Method 2**	
Trial	Hs (m)	K_D	Hs (m)	K_D
1st	6.41	7.32	6.24	6.74
2nd	6.29	6.91	6.47	7.52
3rd	6.56	7.82	6.27	6.85
4th	6.45	7.45	6.53	7.71
5th	6.61	8.02	6.50	7.60
Average	6.46	7.50	6.40	7.28
Standard dev.	0.11	0.39	0.12	0.41
Coefficient of variation	0.018	0.052	0.019	0.056

The two different placement methods of Tetrapod resulted in similar stability coefficient. Therefore, it could be concluded that the stability of Tetrapod does not much depend on the placement methods if regular placement methods are used. However, the stability coefficients for regular placement methods are somewhat larger than the value of 7.0 proposed in the SPM for random placement. This indicates that different stability coefficients should be used depending on the placement method in the design of a breakwater. The results for different placement methods are summarized in Figure 4.3 and Table 4.3.

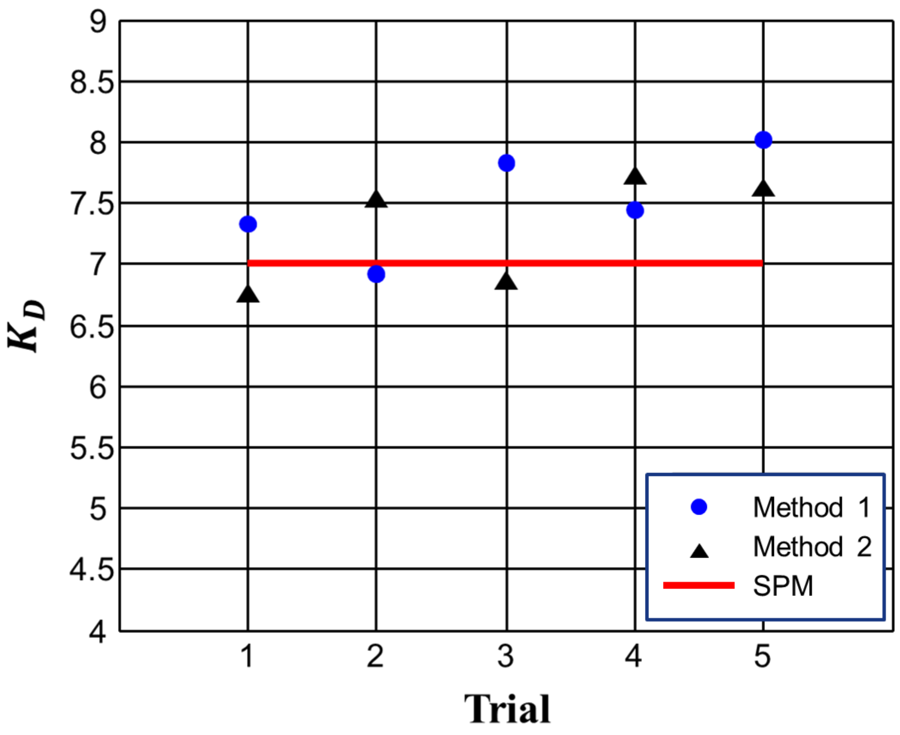


Figure 4.3 K_D-values of SPM and present tests of Tetrapod

Table 4.3 K_D-values of SPM and average of present tests of Tetrapod

	SPM	**Method 1**	**Method 2**
Armor Unit	Tetrapod		
Placement	Random	Regular	
Layers	2		
K_D	**7**	**7.50**	**7.28**

4.2 Rakuna-IV

Since the Rakuna-IV's are in similar shape as the Tetrapods, they were placed in a similar method as the regular placement of Tetrapods (see Figures 4.4 and 4.5). Again the tests were repeated five times under the same wave condition (Table 4.4) and the average stability coefficient was computed. In the Method 1, damage started to occur at the wave height of 5.95 m which gives the stability coefficient of 10.60. In the Method 2, damage started to occur at the wave height of 5.88 m which gives the stability coefficient of 10.18. In common with Tetrapods, the Method 1 is slightly more stable than the Method 2. More detailed experimental results are given in Table 4.5.

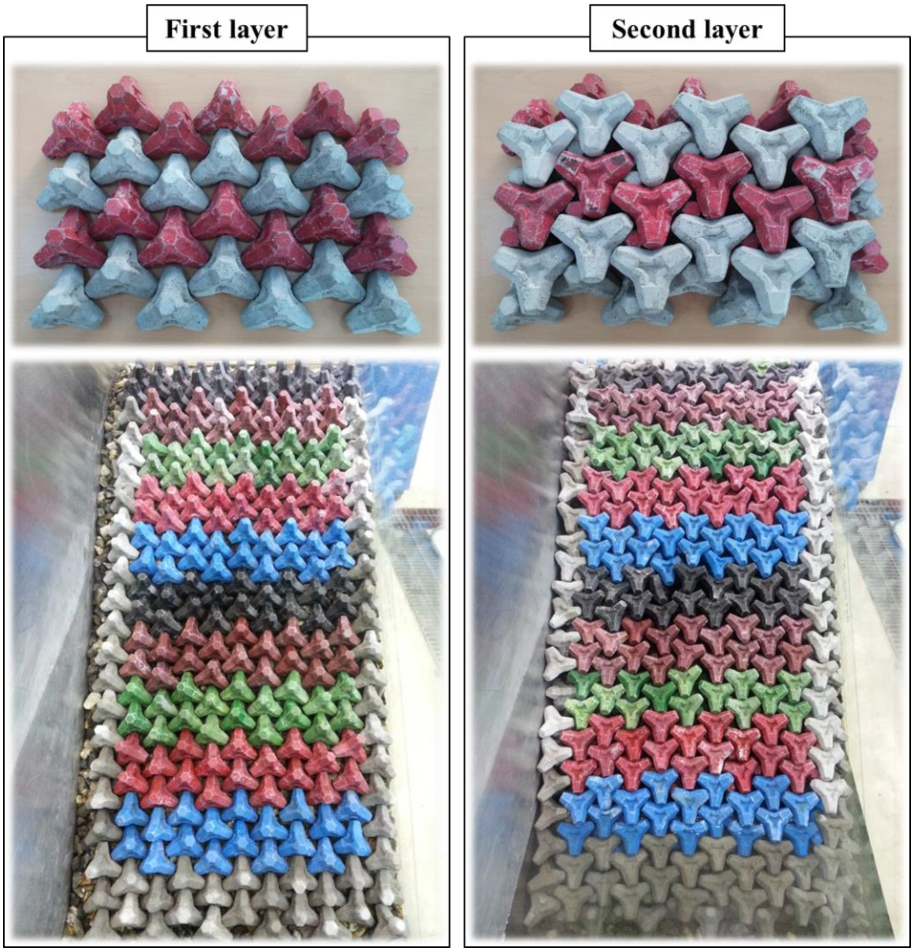


Figure 4.4 Placement method 1 of Rakuna-IV (Porosity: 59 %)

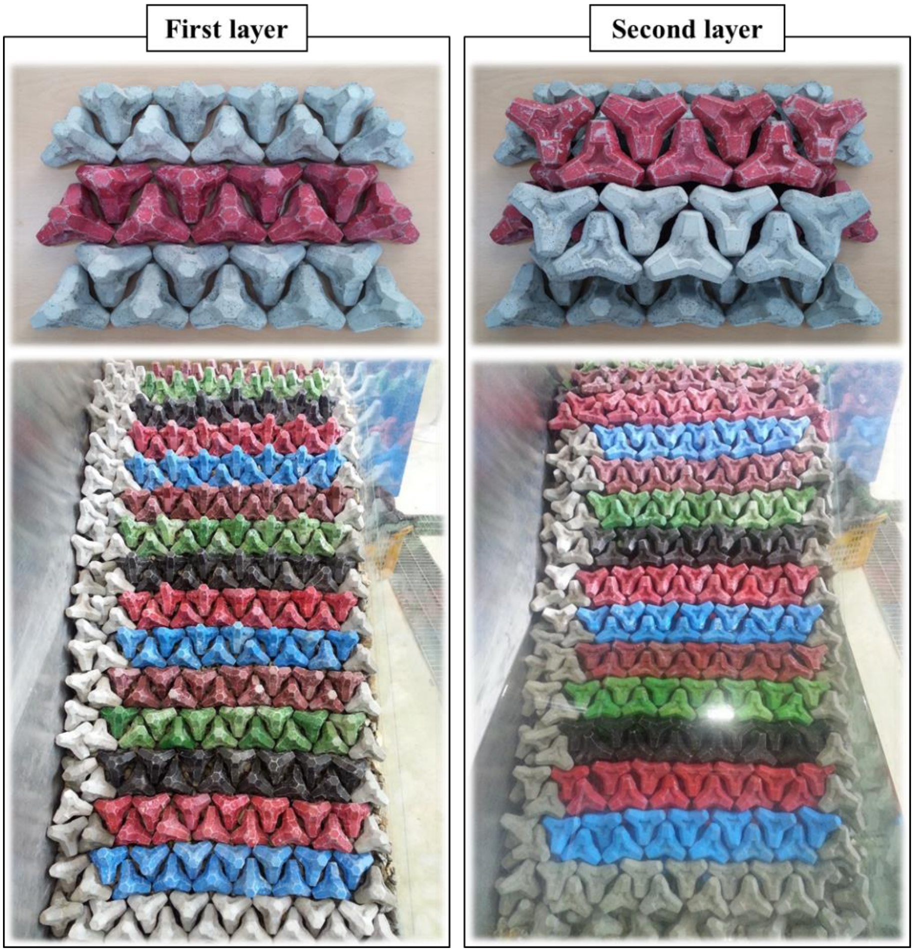


Figure 4.5 Placement method 2 of Rakuna-IV (Porosity: 57 %)

Table 4.4 Wave conditions of Rakuna-IV (scale 1:50)

	Field	Experiment
T_s	13 s	1.84 s
H_s	5.4 m ~ 6.4 m	10.8 cm ~ 12.8 cm
Weight	16 ton class (15.89 ton)	127.1 g

Table 4.5 Comparison of stability coefficients (K_D) between two different placement methods of Rakuna-IV

	Method 1		**Method 2**	
Trial	Hs (m)	K_D	Hs (m)	K_D
1st	5.95	10.58	5.98	10.69
2nd	5.91	10.37	5.85	10.00
3rd	6.01	10.89	5.83	9.91
4th	5.93	10.49	5.84	9.94
5th	5.97	10.67	5.92	10.35
Average	5.95	10.60	5.88	10.18
Standard dev.	0.03	0.18	0.06	0.30
Coefficient of variation	0.006	0.017	0.010	0.030

The Rakuna-IV, like the Tetrapod, does not show significant difference in stability coefficient depending on the placement method if regular placement methods are used. In addition, the stability coefficient of Rakuna-IV is larger than that of Tetrapod.

4.3 Dimple

Since the Dimple also has a shape of tetrahedron like Tetrapod and Rakuna-IV, two different regular placement methods were proposed as shown in Figures 4.6 and 4.7. The placement methods of the first layer are the same in both methods. The placement in the second layer is where the two methods differ. In the Method 1, one leg of the Dimple is directed inwards and is at a right angle to the breakwater slope, and one of the remaining three legs points upwards. In the Method 2, however, one of the remaining three legs points downwards. Different wave heights were used for different placement methods as shown in Table 4.6 because the two methods showed quite different stability. The average stability coefficient obtained from five times repetition of tests was 19.62 for the Method 1, with the corresponding wave height of 7.79 m. For the Method 2, however, no damage occurred at the maximum wave height that could be generated in the wave tank used in this study. The maximum wave height was 8.31 m and the corresponding stability coefficient is 23.80. Therefore, the stability coefficient of Dimple for the placement method 2 should be greater than 23.8. The Dimple shows much higher stability coefficients than the Tetrapod or Rakuna-IV, especially for the placement method 2.

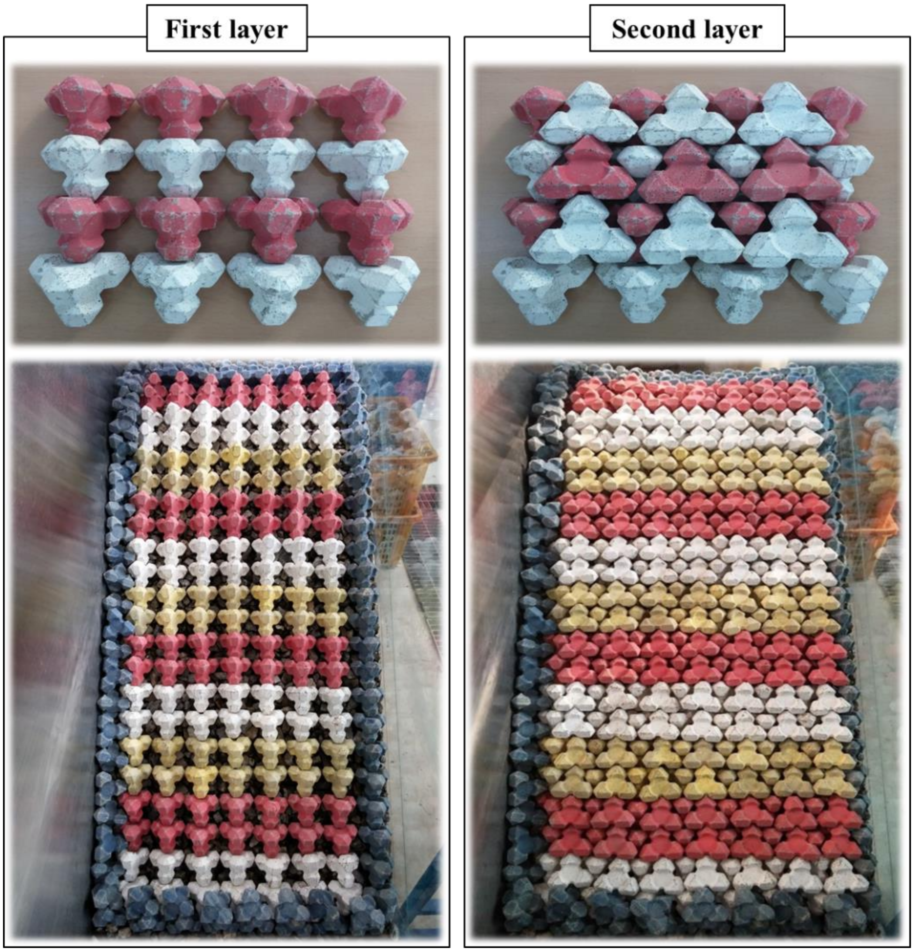


Figure 4.6 Placement method 1 of Dimple (Porosity: 44 %)

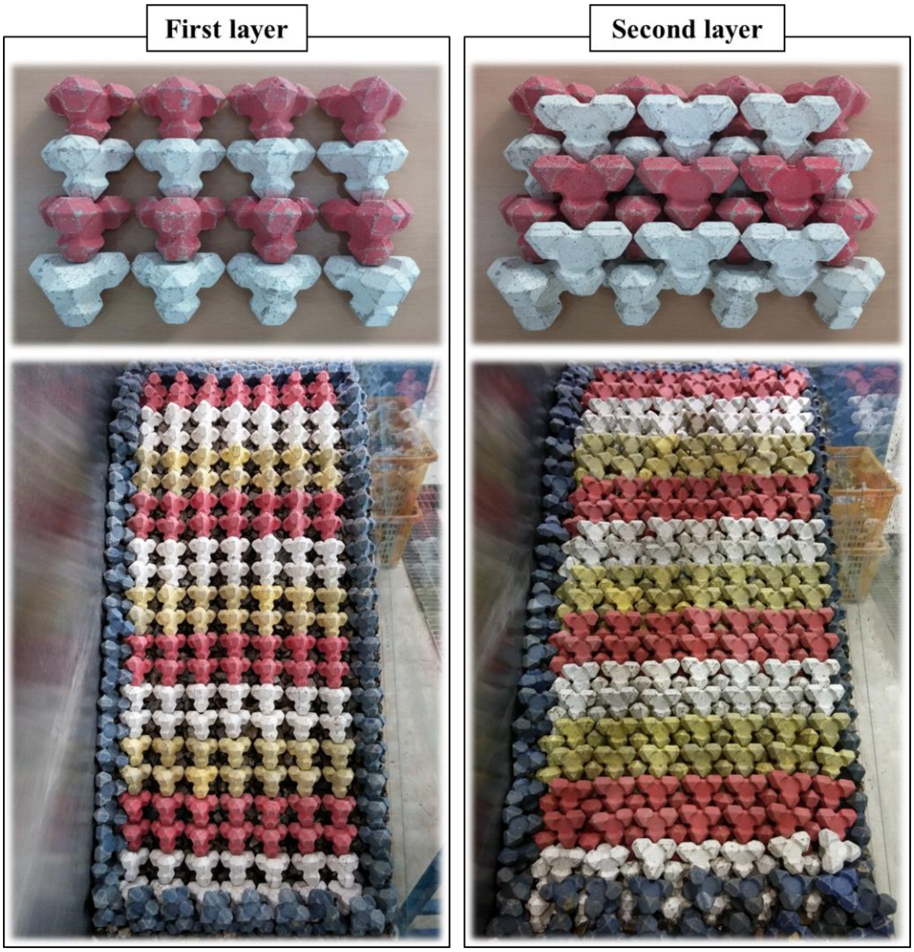


Figure 4.7 Placement method 2 of Dimple (Porosity: 44 %)

Table 4.6 Wave conditions of Dimple (scale 1:50)

		Field	Experiment
T_s		13 s	1.84 s
H_s	Method 1	7.4 m ~ 8.2 m	14.8 cm ~ 16.4 cm
	Method 2	7.6 m ~ 8.4 m	15.2 cm ~ 16.8 cm
Weight		20 ton class (19.28 ton)	151.0 g

Table 4.7 Comparison of stability coefficients (K_D) between two different placement methods of Dimple

	Method 1		**Method 2**	
Trial	Hs (m)	K_D	Hs (m)	K_D
1st	7.80	19.64	8.27	23.42
2nd	7.76	19.36	8.33	23.96
3rd	7.78	19.55	8.26	23.38
4th	7.79	19.59	8.35	24.10
5th	7.84	19.96	8.35	24.15
Average	7.79	19.62	8.31	over 23.80
Standard dev.	0.03	0.20	0.04	0.33
Coefficient of variation	0.003	0.010	0.005	0.014

4.4 Grasp-R

The Grasp-R has a quite different shape from the Tetrapod, Rakuna-IV, or Dimple, and only one placement method is used as shown in Figure 4.8. The average stability coefficient obtained from five times repetition of tests is 25.72 with the corresponding wave height of 7.98 m. Detailed wave condition and test results are shown in Tables 4.8 and 4.9. The Grasp-R is the most stable among the armor units tested in this study.

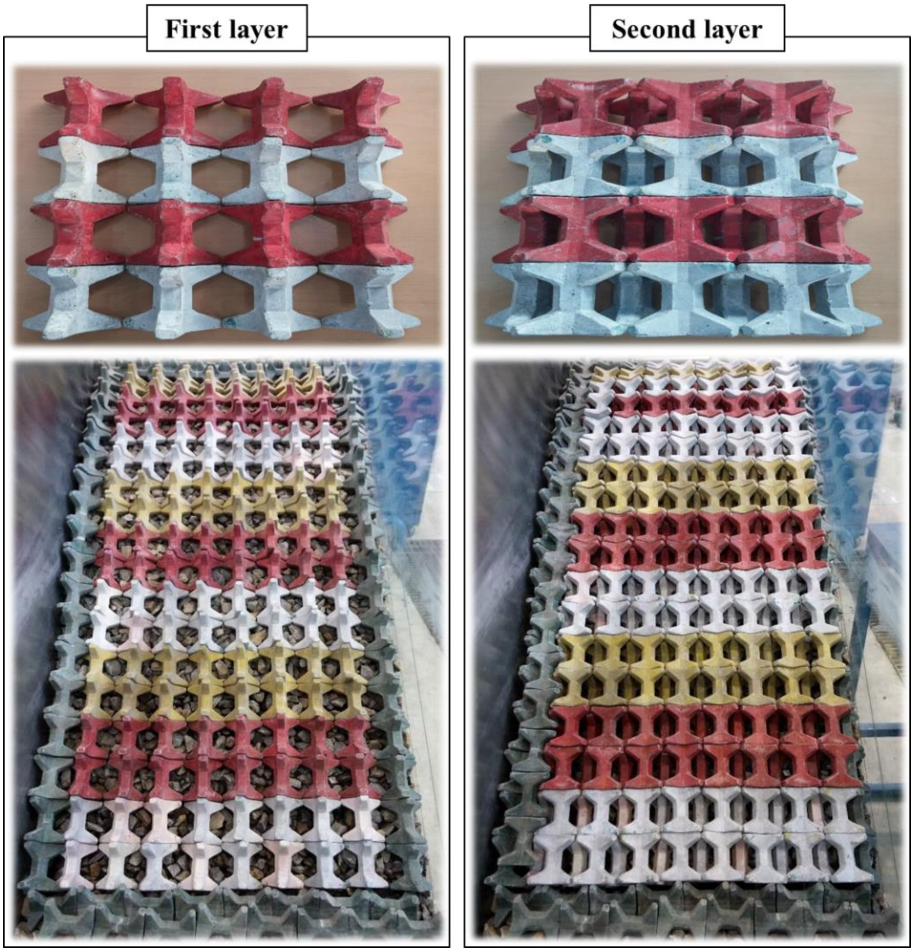


Figure 4.8 Placement method of Grasp-R (Porosity: 62 %)

Table 4.8 Wave conditions of Grasp-R (scale 1:50)

	Field	Experiment
T_s	13 s	1.84 s
H_s	7.6 m ~ 8.4 m	15.2 cm ~ 16.8 cm
Weight	16 ton class (15.82 ton)	128.1 g

Table 4.9 Stability coefficients (K_D) of Grasp-R

Trial	Hs (m)	K_D
1st	8.02	26.12
2nd	7.91	24.99
3rd	7.99	25.75
4th	8.02	26.05
5th	7.98	25.67
Average	7.98	25.72
Standard dev.	0.04	0.40
Coefficient of variation	0.005	0.016

5 Conclusion and Future studies

5.1 Conclusion

In the present study, hydraulic experiments were conducted to estimate the stability coefficients of various armor units placed on a rubble mound breakwater. The regular placement methods were proposed for Tetrapod, Rakuna-IV, Dimple, and Grasp-R, and the stability coefficient for each method was presented. The placement methods and the stability coefficients are summarized in Tables 5.1 and 5.2, respectively.

For the Tetrapod, it was shown that the regular placement gives slightly greater stability coefficient than that given in the SPM for random placement. The Tetrapod and Rakuna-IV did not show much difference in the stability coefficient depending on the placement methods, whereas the Dimple showed quite some difference between different placement methods. Among the armor units of the shape of tetrahedron, the Dimple is the most stable, the Rakuna-IV being the next, and the Tetrapod is the least stable. The Grasp-R, which has a quite different shape from other armor units, showed the greatest stability coefficient among the armor units tested in this study.

Table 5.1 Placement methods of armor units

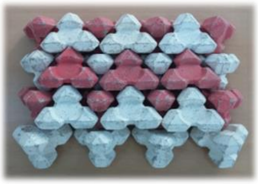
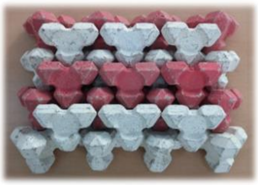
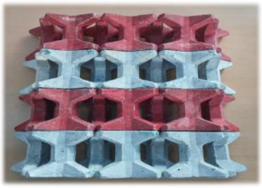
		First layer	Second layer
Tetrapod	Method 1		
	Method 2		
Rakuna-IV	Method 1		
	Method 2		
Dimple	Method 1		
	Method 2		
Grasp-R			

Table 5.2 Stability coefficients depending on placement methods

	Method 1	Method 2
Tetrapod	7.50	7.28
Rakuna-IV	10.60	10.18
Dimple	19.62	23.80
Grasp-R	25.72	

5.2 Future studies

In the present study, only one structure slope of $\cot\theta = 1.5$ and a fixed wave period of 13 s in prototype were used, without considerations to the wave period and cross-sectional variation, which may influence the stability of a breakwater. Additional experiments considering such variables may be necessary for more detailed investigation of optimal placement methods and weight estimation of armor units.

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초 록

경사식 방파제는 오랜 기간 동안 많은 경험을 통하여 축조기술이 발전되어 왔기 때문에 우리나라뿐만 아니라 전 세계적으로 가장 널리 사용되고 있다. 경사식 방파제에 피복되는 피복재는 입사하는 파랑에 의해 파괴 또는 이탈되지 않을 강도 및 중량을 가진 사석 또는 콘크리트 소파블록으로 이루어진다. 안정한 설계를 위해 여러 연구자들이 소파블록의 적정 중량을 산정하기 위하여 많은 연구를 수행하여 왔다. Hudson (1959)은 다양한 소파블록의 적정 중량 산정을 위해 안정계수(K_D)를 포함하는 공식을 제안하였다. 테트라포드를 비롯한 다양한 소파블록에 대한 안정계수는 U.S Army Corps of Engineers에서 발행한 Shore Protection Manual에 제시되어 있으나, 한정된 파랑조건과 단면조건에서의 실험으로 인해 그 적용성의 한계점을 가지고 있다.

본 연구에서는 경사식 방파제에 소파블록을 피복하는 방법과 그에 따른 안정계수(K_D) 값을 제시한다. 소파블록으로는 우리나라에서 가장 많이 사용되고 있는 테트라포드를 비롯하여 Rakuna-IV, Dimple, 그리고 Grasp-R을 이용하였다. 국내에서 가장 빈번히 사용되는 경사

1:1.5의 경사식 방파제를 대상으로 하였으며, 우리나라에서 주로 사용하고 있는 정적 피복 방법을 제안하였다. 안정계수는 우리나라에서 소파블록의 적정 중량 계산에 널리 사용되는 Hudson(1959)식에서 유도하였다. 그 결과 테트라포드와 Rakuna-IV는 2가지 정적 피복 방법을 제안하였으며, 안정계수는 피복 방법에 상관없이 비슷하였다. Dimple 역시 2가지 정적 피복 방법으로 실험을 수행한 결과, 두 방법의 차이가 컸다. Grasp-R에 대해서는 한가지 정적 피복 방법을 사용하였으며, 다른 소파블록들보다 큰 안정계수를 나타내었다.

주요어: 경사식방파제, 피복 방법, Tetrapod, Rakuna-IV, Dimple, Grasp-R, 안정계수

학번: 2013-20926