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An Experimental Study on the Stability of Temporary Armor Unit for Revetment against Wave

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Abstract: When a coastal structure has significant damage by a huge typhoon, an emergency response is required to prevent the deterioration of the damage, such as covering temporary armor units on the damaged part. Gabions, Stone filled fiber nets and Sandbags are used as temporary armor units, which can be rapidly manufactured and installed in Japan. However, the stability coefficients (e.g. K_D and N_s coefficients) were scattered by previous studies causes difficulty of design. We conducted hydraulic experiments in the same experimental conditions for these units against waves. As a result of the experiment, it was revealed that the stability of the gabions and the stone filled fiber nets were almost the same. In contrast, the stability of sandbags was relatively low.

Keywords: Temporary armor unit, Stability against wave, Hydraulic model experiment, Stone filled fiber net, Gabion, Sandbag

1 Introduction

When a coastal structure has significant damage by a disaster such as a big typhoon, an emergency response is required to prevent the deterioration of the damage, such as covering temporary armor units on the damaged part. They are expected to keep sufficient durability against the high waves until completely restoring the structure. The following materials are usually used as the armor units; Sandbags, Gabions, or Stone filled nets made of synthetics fiber (hereafter referred to as SFN). Fig. 1 shows them placed in the field. They are easy to be prepared only by packing sand and stone, in addition, they can be quickly laid on the target sites more than concrete blocks.

Gabions stability under the water was confirmed a study by Hiraishi (2016). However, there are few studies in Japan except it. There are a few stability studies against waves on SFNs (e.g. Shimabukuro et al. (2006) or Kuroda et al. (2014)). However, K_D coefficients proposed by several manufacturers are different, despite that their structures and materials are almost the same. To clarify the stabilities of these units, we conducted a series of hydraulic experiments.

Fig. 1. Temporary armor units at the actual place (left: SFNs, center: Gabions, right: Sandbags).

2 Procedure of the Hydraulic Model Experiment

2.1 The Facility

A series of experiments was carried out using the 105m wave flume in the port and airport research institute in Japan. Fig. 2 shows the plan view of the flume. It has a length of 105 m, a width of 3.0 m and a height of 2.5 m. The wave flume is separated into a main flume with 0.8 m wide and a secondary flume with 2.05 m wide at the position with a 42m distance from the wave generator,

The piston type wave generator can produce approximately 1 to 10 second period waves. In this experiment, irregular waves were generated.

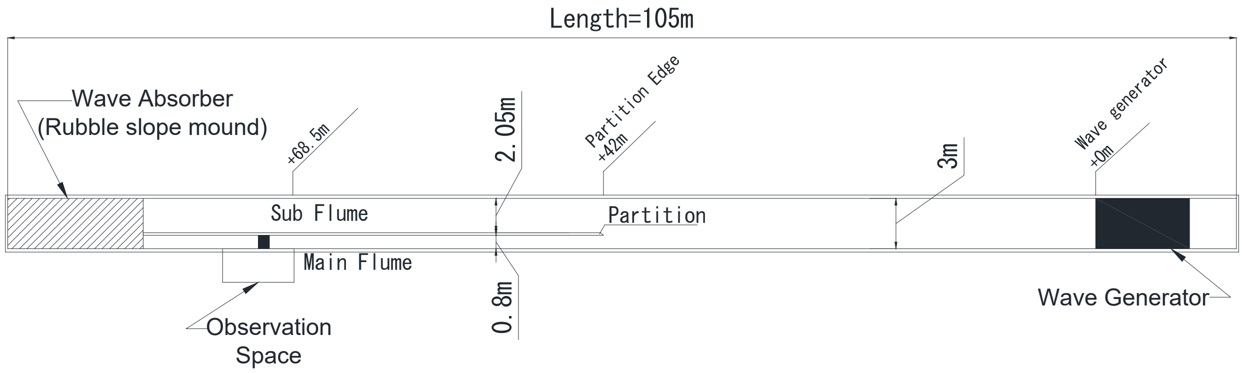


Fig. 2. Plan view of the wave flume.

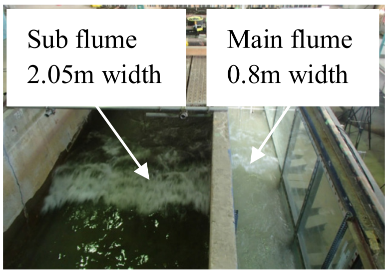


Fig. 3. The main flume and the sub flume.

Fig. 4. Wave generator.

2.2 Temporary Armor Unit Models

Gabion, SFN and sandbag were tested as temporary armor units. Wave-dissipating block (Tetrapod) was also tested as armor units to compare the stabilities. The sandbag used in this experiment is a flexible container bag that is easily handled in a field. The sandbag used in this study is vertically long as shown in Fig. 1 and frequently used in Japan.

Tab. 1 shows the size and the mean mass of the experimental models, which are the average value of 10 samples. Each model was made at about 500 g for comparison. The mass of sandbags used in the field is 2t.

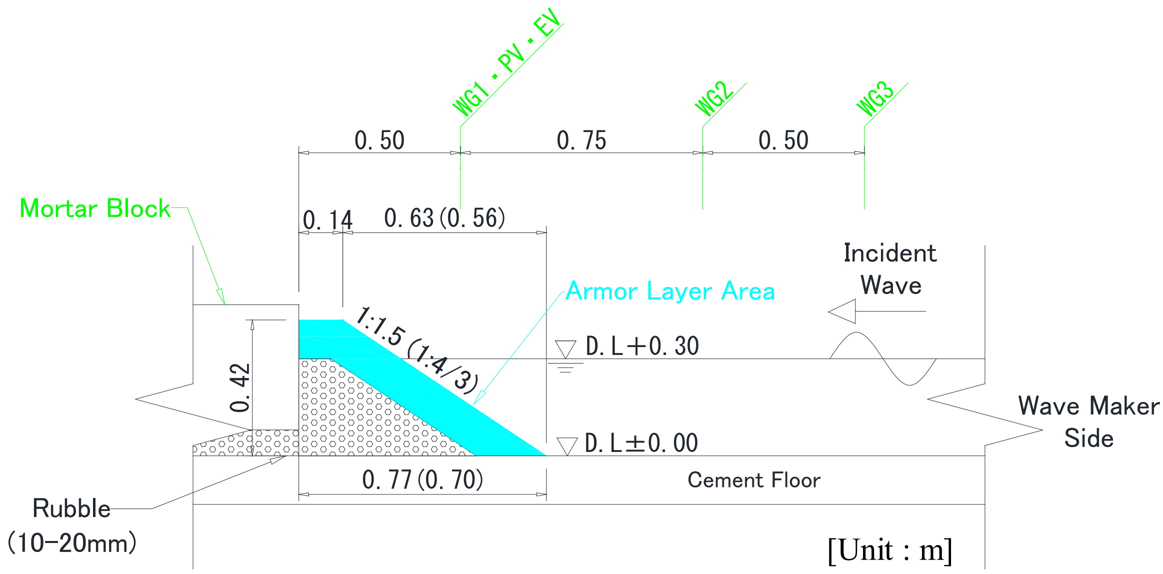
Tab. 1. Size and mean mass in each model of armor units

Model Types	 Gabion	 SFN	 Sandbag	 Wave dissipating block
Mean Mass (g)	499	507	584*	444
d : Height (cm)	4.0	3.5	7.2	9.0
l : Length (cm)	12.0	13.0	7.2	9.7
w : Width (cm)	7.5	13.0	7.2	10.8

*Measured in wet condition

2.3 Cross-section of the experiment

Fig. 5 shows the cross section of the experiment. A trapezoidal rubble mound made of 10-20mm stones was installed in front of a mortar block. The slope of gabion, SFN and sandbag was set as 1: 1.5. The slope of wave dissipating blocks was set as 1:4/3. To compare with the wave dissipating blocks, SFNs was also tested at the same gradient with the wave dissipating blocks.The water depth at the toe of the slope was 0.3m.



WG: Wave Gage PV: Propeller Velocity meter EV: Electromagnetic Velocity meter

Fig. 5. Experimental cross-section and measurement device position.

2.4 Laying method of the temporary armor units

Two types of laying methods were examined, referring to Shimabukuro et al. (2006). One of laying methods is to lay the units without overlapping (hereafter referred as ‘flat condition’). The other is to lay the units with overlapping (hereafter referred as ‘overlap condition’).

Fig. 6 shows examples of these methods. The left photos in Fig. 6 show the overlapped SFNs and the right photos show the non-overlapped SFNs.

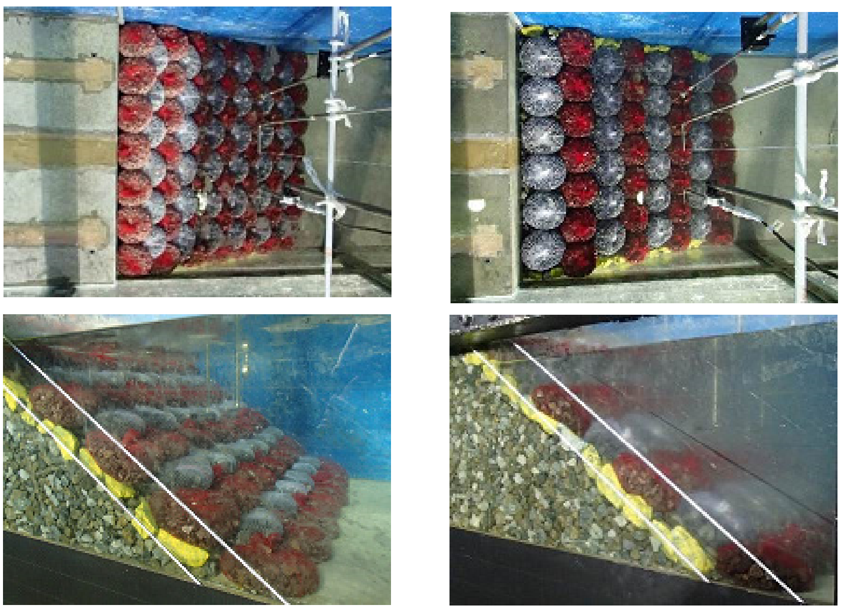


Fig. 6. Laying methods of SFNs (Left: Overlapped condition, Right: Non-overlapped condition).

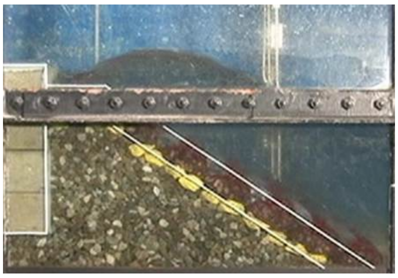
2.5 Wave Conditions

We used irregular waves which was made in accordance with the Bretschneider-Mitsuyasu spectrum.
Wave periods (*T*) were set as 1.5s and 2.5s. Wave height (*H*) was gradually increased until the units were damaged by waves. The number of waves was 1,000.

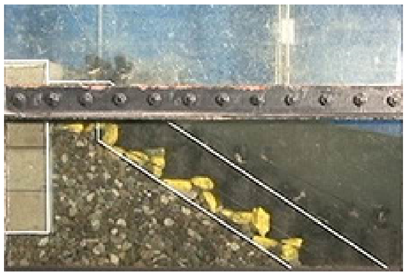
3 Result of the Experiment

Fig. 7 shows the snapshots during wave action. As wave height increased, the position of wave action changed from the slope to the crest.

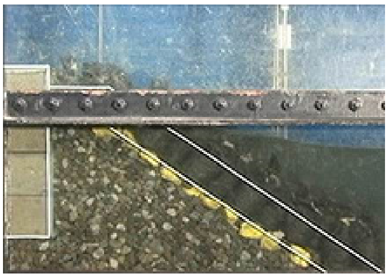
a. SFNs: Overlapped



b. Gabions: Overlapped

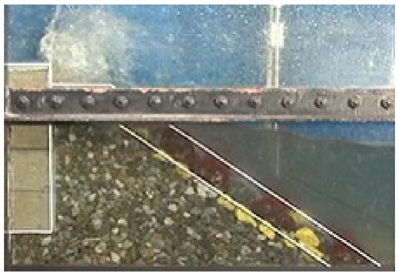


c. Sandbags: Overlapped



d. SFNs: Non-overlapped

e. Gabions: Non-overlapped



f. Sandbags: Non-overlapped

Fig. 7. Snapshots during wave action.

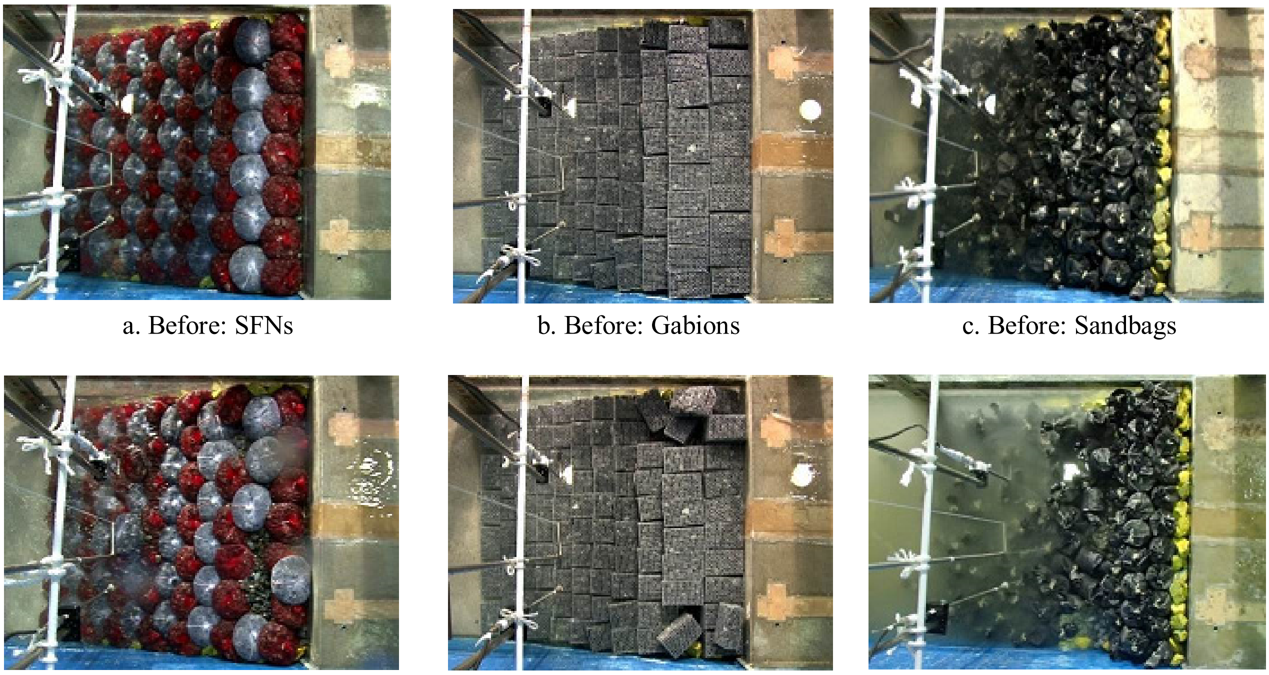
Fig. 8 and Fig. 9 show the damage of the temporary armor units before and after the wave actions for overlapped and non-overlapped condition, respectively. The damage of the overlapped armor units was different from that of non-overlapped condition.

In the cases of the gabions and the sandbags, the non-overlapped units slipped at one time by receding waves because the toe of the slope was not fixed to the bottom floor.

In the case of the SFNs, after deformation of SFNs, rubbles under the SFNs were exposed and washed away, resulting in the large movement of SFNs. High flexibility of SFNs caused the expansion of the gap between the SFNs.

On the other hand, damage of the overlapped units was smaller than that of the non-overlapped condition. We supposed that the overlapping increased the armor unit thickness and interlocking, resulting in the increase of stability.

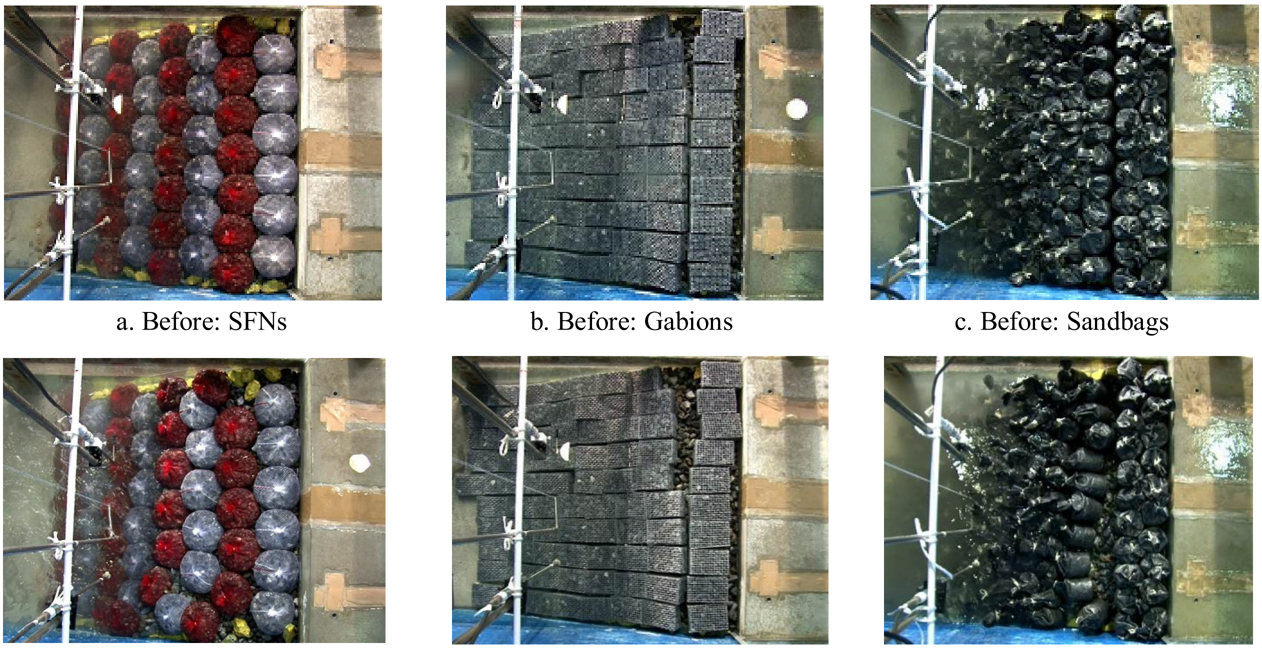
Fig. 10 shows a snapshot during wave action in wave dissipating blocks condition, and the damage of their before and after wave actions. In the experiment, Wave dissipating blocks were installed two layers on the slope. Although the surface side layer blocks of the crest portion moved, the backfill material was not exposed.



a. Before: SFNs b. Before: Gabions c. Before: Sandbags

d. After: SFNs e. After: Gabions f. After: Sandbags

Fig. 8. Damage of the overlapped armor units before and after the wave action.



a. Before: SFNs b. Before: Gabions c. Before: Sandbags

d. After: SFNs e. After: Gabions f. After: Sandbags

Fig. 9. Damage of the non-overlapped armor units before and after the wave action.

a. Snapshot b. Before wave action c. After wave action

Fig. 10. Snapshot and damage of wave dissipating blocks before and after wave action.

4 Discussion

4.1 K_D value

Here, we compared the stability of the temporary armor units by K_D value of Hudson formula (1959) which expressed as equation 1 and 2.

$$M = \rho_r H^3 / (K_D (S_r - 1)^3 \cot\alpha) \tag{1}$$

$$N_s^3 = K_D \cot\alpha \tag{2}$$

where M = mass of an armor unit, ρ_r = armor unit density, H = design wave height at the structure site, N_s = stability number, S_r = specific gravity of armor unit, α = angle of structure slope measured from horizontal, and K_D = stability coefficient that varies primarily with the shape of the armor units, roughness of the armor unit surface, sharpness of edges, and degree of interlocking obtained in placement. In this study, H is incident wave component measured at WG2-3.

Fig. 11 shows the K_D values of the wave dissipating blocks and the SFNs. Wave dissipating block was more stable than SFN at a 3% damage rate. The steeply installed SFN ($\cot\theta$=4/3) was more stable than the mildly installed SFN ($\cot\theta$=1.5). Here, we defined the damage rate as the ratio of the number of the damaged model and the number of the all installed models. We also was defined the damage as the movement of models by half of the model size or the rotation by 90 degrees.

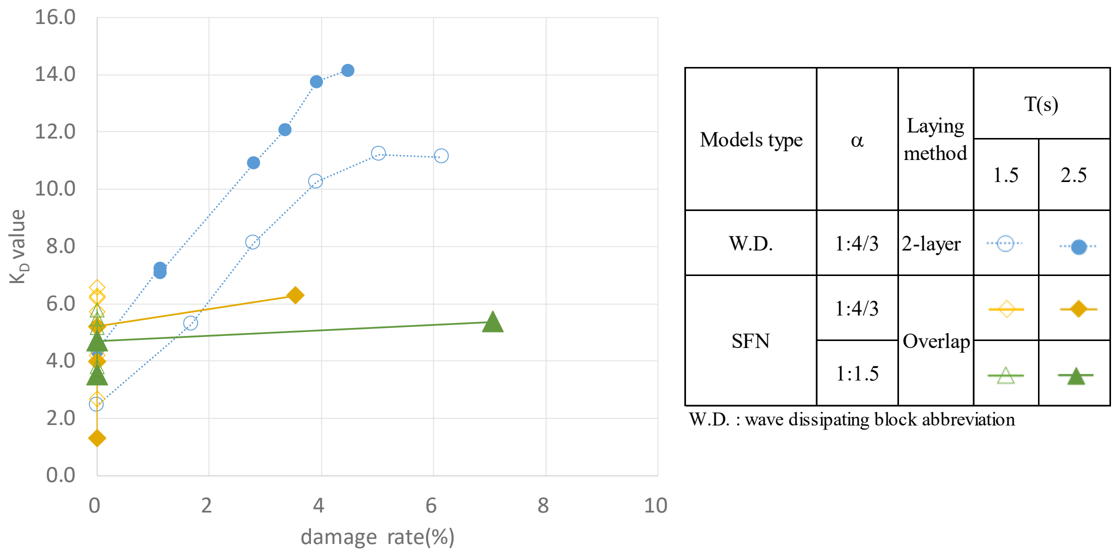


Fig 11. Relation between K_D value and damage rate (Wave dissipating blocks and SFNs).

Tab. 2. K_D values of Wave dissipating block and SFN in Fig. 10.

Models type	ρ_r (kg/m^3)	S_r	M (g)	α	T(s)	K_D value (Significant wave height (cm) , Damage rate(%))						
W.D.	2300	2.3	444	1:4/3	1.5	2.5 (10.6 , 0)	5.3 (13.7 , 0.7)	8.1 (15.8 , 2.8)	10.3 (17.0 , 3.9)	11.2 (17.5 , 5.0)	11.1 (17.5 , 6.1)	-
					2.5	4.4 (12.8 , 0)	7.2 (15.2 , 1.1)	7.1 (15.1 , 1.1)	10.9 (17.4 , 2.8)	12.1 (18.0 , 3.4)	13.7 (18.8 , 3.9)	14.1 (19.0 , 4.5)
SFN	2600	2.6	507	1:4/3	1.5	2.7 (13.5 , 0)	4.2 (15.7 , 0)	5.2 (16.8 , 0)	5.7 (17.4 , 0)	6.2 (17.9 , 0)	6.3 (17.9 , 0)	6.6 (18.2 , 0)
					2.5	1.3 (10.7 , 0)	4 (15.4, 0)	5.2 (16.9 , 0)	6.3 (16.9 , 3.5)	-	-	-
				1:1.5	1.5	5.2 (17.5 , 0)	5.5 (17.8, 0)	3.8 (15.8 , 0)	5.8 (18.2 , 0)	-	-	-
					2.5	3.5 (15.4 , 0)	4.7 (17.0 , 0)	5.4 (17.7 , 7.1)	-	-	-	-

Fig. 12 shows the relation between the damage rate and K_D values of temporary armor units. The overlapped units was more stable than the non-overlapped units. K_D values of sandbags was extremely smaller than those of others. In this experiment, since the toe of the slope is not protected, the result is possible to change if it is protected.
Tab. 4 shows K_D values of those units at a 3% damage rate.

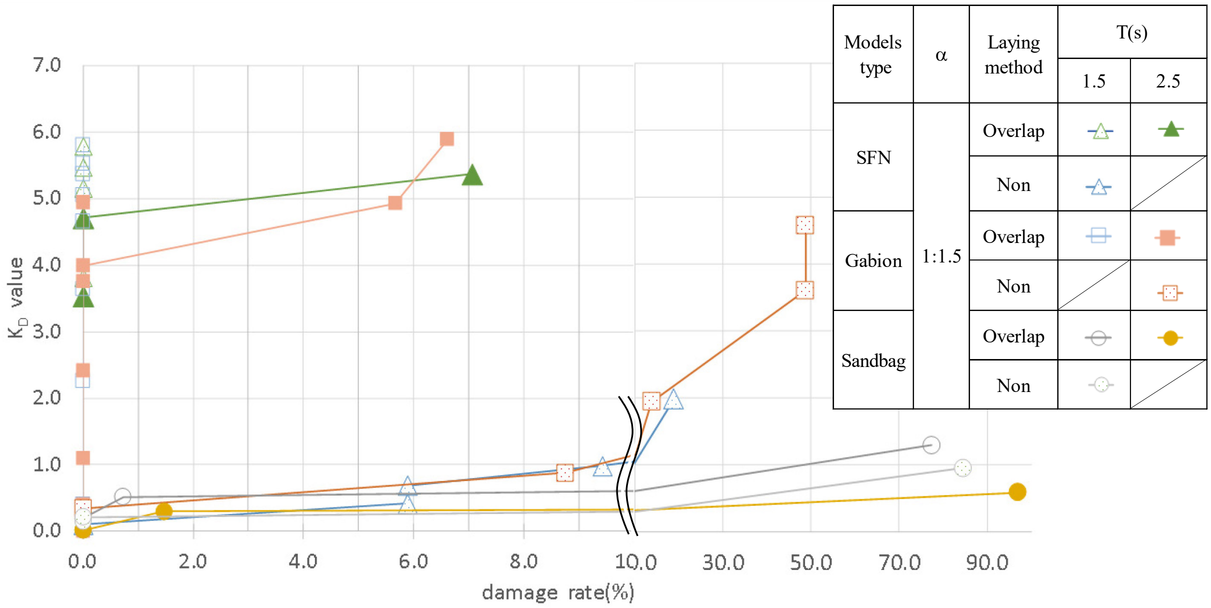


Fig 12. Relation between K_D value and damage rate (Temporary armor units).

Tab. 3. K_D values of temporary armor units in Fig. 11.

Models type	ρ_r (kg/m^3)	S_r	M (g)	α	Laying method	T(s)	K_D value (Significant wave height(cm) , Damage rate(%))								
SFN	2600	2.6	507	1:1.5	Overlap	1.5	5.2 (17.5 , 0)	5.5 (17.8, 0)	3.8 (15.8 , 0)	5.8 (18.2 , 0)	–	–	–	–	–
						2.5	3.5 (15.4 , 0)	4.7 (17.0 , 0)	5.4 (17.7 , 7.1)	–	–	–	–	–	–
					Non	1.5	0.1 (4.2 , 0)	0.3 (7.0 , 5.9)	0.6 (8.4 , 5.9)	0.9 (9.6 , 9.4)	1.6 (11.8 , 18.8)	–	–	–	–
Gabion			499		Overlap	2.5	0.1 (5.0 , 0)	0.4 (7.4 , 0)	1.1 (10.4 , 0)	2.4 (13.5 , 0)	3.8 (15.6 , 0)	4.9 (17.1 , 0)	4.0 (16.0 , 0)	4.9 (17.1 , 5.7)	5.9 (18.2 , 6.6)
						1.5	0.4 (7.4 , 0)	2.3 (13.2 0)	3.6 (15.5 , 0)	4.7 (16.8 , 0)	5.0 (17.3 , 0)	5.4 (17.6 , 0)	5.5 (17.8 , 0)	5.8 (18.1 , 0)	–
					Non	2.5	0.3 (7.1 , 0)	0.9 (8.8 0)	1.9 (12.6 , 13.8)	3.6 (15.4 , 48.8)	4.6 (16.7 , 48.8)	–	–	–	–
Sandbag	1900	1.9	584		Overlap	2.5	0.0 (1.7 , 0)	0.3 (4.3 , 1.5)	0.6 (5.5 , 97.1)		–	–	–	–	–
						1.5	0.0 (1.8 , 0)	0.2 (3.8 , 0)	0.5 (5.2 , 0.7)	1.3 (7.1 , 77.4)	–	–	–	–	–
					Non	1.5	0.1 (3.5 , 0)	0.2 (3.9 , 0)	0.9 (6.4 , 84.6)	–	–	–	–	–	–

Tab. 4. K_D values of temporary armor units at 3%damage rate

Models Type	Gabion (Overlap)	SFN (Overlap)	Sandbag (Overlap)	Wave dissipating block (2-layer)
Gradient α	1:1.5	1:1.5	1:1.5	1:4/3
Wave period (sec)	2.5	2.5	2.5	1.5
K_D value	4.4	4.9	0.3	8.5

4.2 *Density of the composite material*

The following two equations (3) and (4) express the density of a composite material. In existing researches (Pilarczyk(2000), Shimosako et al.(2004), Arikawa et al.(2013)), the equation (3) is used to express the density of gabion and SFN, and the other is used for sandbag. Tab. 5 shows the densities calculated by the two equations. In the case of SFN, the density calculated by the equation (4) is 20% smaller than that calculated by the equation (3). If we use the density calculated by the equation (4), the stability number estimated by experiments becomes apparently larger. Density also depends on the water saturation of the armor units. The density of these armor units has not been sufficiently studied, therefore further studies are needed.

$$\Delta = (\rho_s - \rho_w) / \rho_w \quad (3)$$

$$\rho_b = \rho_s (1 - n) + \rho_w (\mathrm{n}) \quad (4)$$

Where Δ = relative density composite material, ρ_s = volumetric mass of material (ρ_b is instead of ρ_s in the case of second method), ρ_w = volumetric mass of water, ρ_b = density definition of the mass density of composite material, n = porosity of material.

Tab. 5. Density values calculated individual methods

Models Type	Gabion	SFN	Sandbag
Volume (cm^3)	360.0	309.6	293.0
Density calculated by equation (3) (kg/m^3)	2600	2600	1900
Density calculated by equation (4) (kg/m^3)	2007	2002	1828

*Saturated density

4.3 *Comparison of the stability relation between wave load and surf similarity parameter*

The experimental results by Porraz et al. (1979) showed that the stability of mortar filled container increases with the steepness of the slope. From these results, Pilarczyk (2000) stated that the Hudson formula is not representative for the stability of large geobags because of the different representation of the slope gradient.

As mentioned previously, Fig. 10 indicates a similar characteristics of SFN, that is, the stability of SFN increases with the steepness of the slope. Here, as in Pilarczyk (2000) and Wouters (1998), we applied a stability number (*Ns*) to our experimental results as follows.

$$N\mathrm{s}=H_s / \Delta D = f(\xi) \quad (5)$$

$$\xi = \tan\alpha / (H_s / L)^{1/2} \quad (6)$$

$$L = gT_p^2 / 2\pi \quad (7)$$

where, H_s = significant wave height at the toe of the structures (m), Δ = relative density of armor unit, D = thickness of armor layer (m), ξ = surf similarity parameter, L = wave length in deep water (m), g = gravitational acceleration (m/s^2), T_p = wave period at the top of the spectrum (s). In this study, H_s is a significant wave height in front of the structure (WG2-3) instead of that at the toe.

T_p is the period that was measured in front of the wave generator (position away from 10 m), Δ is calculated by the equation (3). Here, we also defined D as shown in Fig. 13.

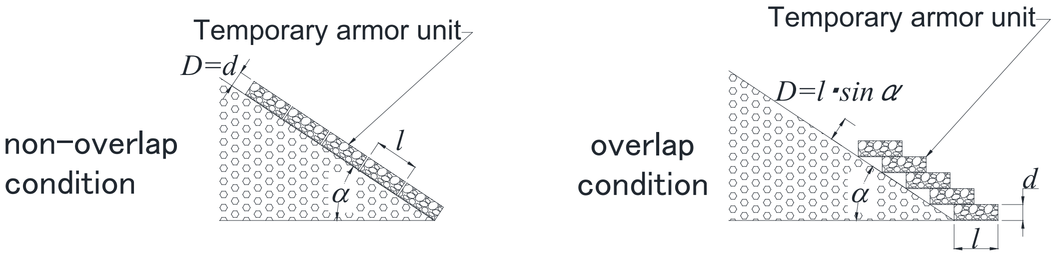


Fig. 13. Definition of armor layer thickness (D).

Fig. 14 shows the relation of Eq. (5) in the case of the SFN and the gabion. These figures indicate that the SFN and the gabion have similar trend.
Fig. 15 shows the relation between H_s / ΔD and ξ of the SFNs and the gabions.
SFN and gabion become unstable when the stability number ($H_s/\Delta D$) is greater than 3.5 / $\xi^{1/2}$.

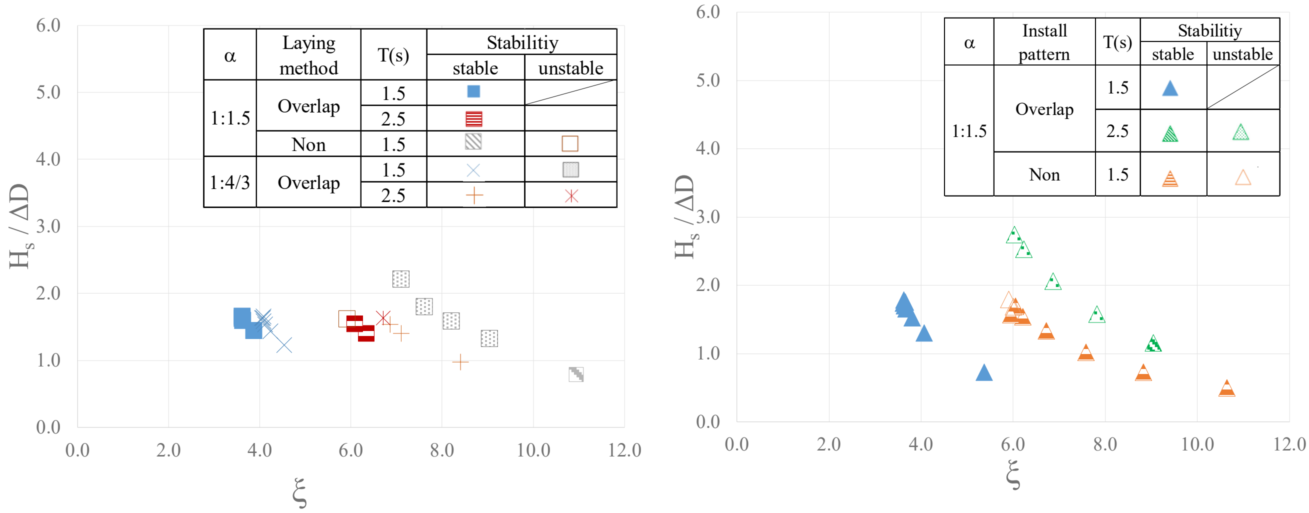


Fig. 14. Relation between H_s / ΔD and ξ (Left: SFN, Right: Gabion).

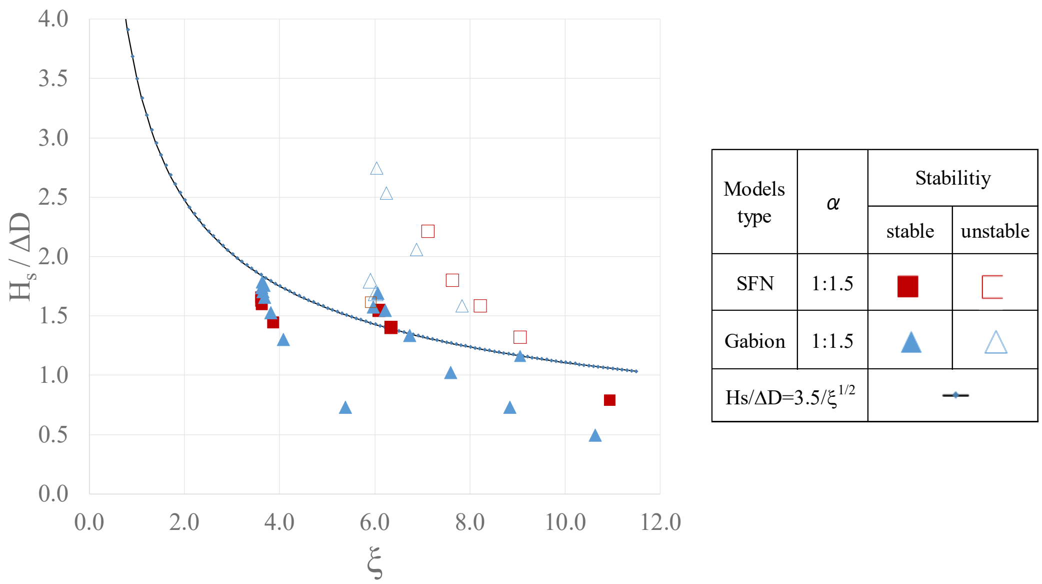


Fig. 15. Relation between H_s / ΔD and ξ of SFN and Gabion.

Fig. 16 shows the relation between H_s / ΔD and ξ of the sandbags. The sandbag becomes unstable when the stability number ($H_s/\Delta D$) is greater than 2.0/$\xi^{1/2}$. This criteria is smaller than the criteria (Ns=2.5/$\xi^{1/2}$) proposed by Woulters (1998) because the sandbag in this study is vertically longer and more unstable than the sandbag used by Woulters.

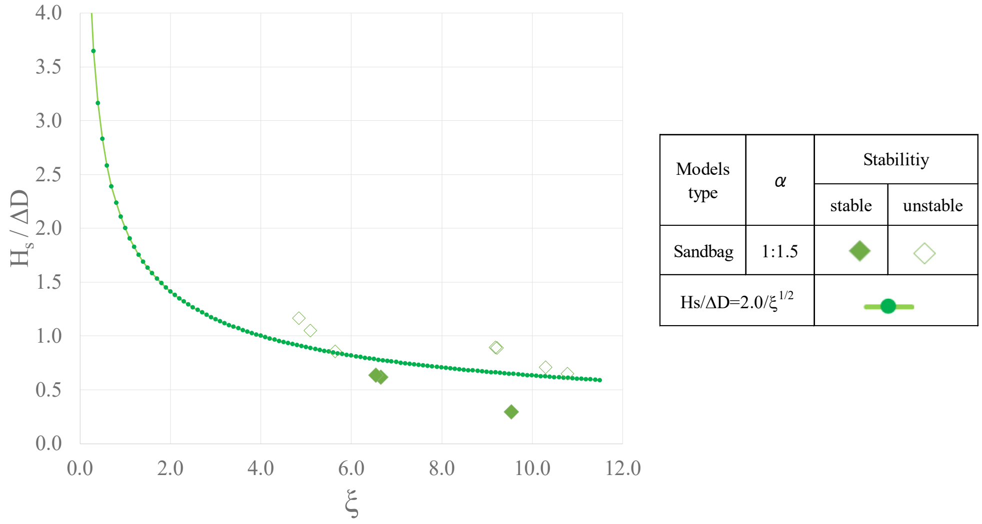


Fig. 16. Relation between H_s / ΔD and ξ of Sandbag.

5 Conclusion

This experimental study confirmed that SFNs and Gabions have almost the same stability and those are more stable than sandbags. K_D values of the SFN, the gabion and the sandbag were 4.9, 4.4 and 0.3, respectively under the condition of the slope gradient 1:1.5. Furthermore, the relation between $H_s/\Delta D$ and functional ξ was also examined using the result of the experiments. It was confirmed that the stabilities of them had the same characteristics as the result of K_D values. However, these experiments were conducted under limited conditions. Therefore, further study is needed regarding more wave conditions, scale effect, sand wash-out from subsoil layer, etc.

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