STABILITY PAERFORMANCE ASSESSMENT OF HONEY COMB SHAPE BLOCKS FOR COASTAL ARMOUR UNITS

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ABSTRACT

Armour blocks are useful and effective as a countermeasure for protecting coastal structures such as composite breakwaters, coastal dikes, artificial reefs and so on. "HONEY-CALM" is a newly developed honeycomb shape armour block. High stability is expected so as to have five hexagonal large apertures to reduce uplift pressure. Economical efficiency is also expected so that reduces amount of concrete due to large porosity against an occupied area. This study conducted a series of hydraulic model experiments to assess the stability performance against wind waves and tsunamis of HONEY-CALM applied to various coastal structures. The experiments of wind waves were conducted on covering of composite breakwater mound, coastal dike slope and artificial reef. The experiments of tsunamis were conducted on covering of raised rubble-mound installed behind a caisson breakwater to evaluate the stability against tsunami flow. The experimental results show stability against waves and tsunamis. HONEY-CALM has significantly higher stability than the other flat-shape armour blocks.

Keywords: Honeycomb-shape, Armour blocks, block stability, hydraulic model experiments

1. INTRODUCTION

Armour blocks are useful and effective as a countermeasure for scouring of coastal structures such as composite breakwaters, coastal dikes and artificial reefs and so on. These coastal defense structures are required to have higher stability for the increase of extreme storm waves due to climate change. At the same time, low costs and economics are required in public works and armour blocks protection works are often valued by economic efficiency. "HONEY-CALM" is a newly developed honeycomb shape armour block with high stability and economy. High stability is expected by five hexagonal large apertures which can reduce uplift pressure. In addition, the cover area is larger than that of other conventional armour block against the same weight. Thus, the cost can be cut down because of reducing the required amount of concrete. Figure 1 shows the specification of HONEY-CALM (4 t type). HONEY-CALM has two types: a normal type and a low-leg type. That is, leg lengths are different. The normal type is used for artificial reefs. The low-leg type is used for composite breakwaters. The installation arrangement is selected as "vertical arrangement" and "horizontal arrangement" as shown in Fig.2. The vertical arrangement is standard; however, the horizontal arrangement is also selected when the number of blocks on crown width is fixed despite of being required for horizontal distance to cover its rubble-mound surface above the sea level.

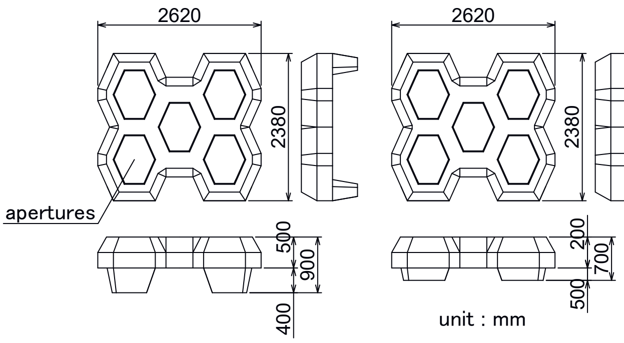
This study conducted a series of hydraulic model experiments to assess the stability performance of HONEY-CALM used to four different types' coastal structures against wind waves and tsunamis. The experiments of wind waves were carried out for covering of composite breakwater mound, coastal dike slope and artificial reef. The experiments of tsunamis were conducted for covering of raised rubble-mound installed behind a caisson breakwater to evaluated the stability against the tsunami overflow.

2. COMPOSITE BREAKWATER MOUND

2.1 Overview of experiment

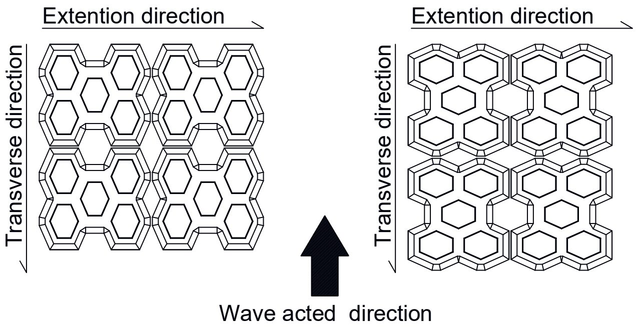
Experiments of a composite breakwater mound were conducted in a wave flume of which size is 50.0 m long, 1.0 m wide and 1.5 m high. A breakwater model was placed on a fixed bed of which foreshore slope is 1/30. Figure 3 shows a cross-section of the composite breakwater mound model. Where B is the slope top, d is the depth from the armour block to still water level, h is the water depth at the toe of breakwater. The caisson was fixed to the flume wall not to move by acting waves. The model scale was 1/50. The weight of a block model was 32.9 g for a normal type 31.3 g for a low-leg type, respectively, and the weight of prototype block is 4 t. Table 1 shows experimental conditions. In the experiments, the B/L_i, (L_i is the significant wavelength at toe of breakwater) was set to four cases of 0.04, 0.08, 0.12 and 0.16. The d/h was set to 0.2, 0.4, 0.6 and 0.8. The installation arrangement of the vertical one was adopted. The incident wave was random waves with the modified Bretschneider-Mitsuyasu spectrum and the wave number acted was 1,000. In each test case, the wave height was increased gradually until blocks were displaced, and the critical wave height was examined. The damage ratio was calculated as the ratio of damaged block number to the total block number. The allowable damage ratio was set to 0%. Table 2 shows the damage form. The damaged block number was counted by comparing the images at the start and end of the test. The block stability number Ns was calculated using the Brebner-Donnelly's formula shown by Eq. (1). Where W is the block mass, ρ_c is the concrete density, H_i is the significant wave at the toe of breakwater, and S_r is the ratio between concrete density and water density.

$$W = \frac{\rho_c \times H^3}{Ns^3 \times (S_r - 1)^3} \tag{1}$$



a) Normal type b) Low-leg type

Fig.1 Specification of HONEY-CALM (4t type)



a) Horizontal b) Vertical

Fig.2 Installation arrangement

Table 1 Test cases for composite breakwater mound experiment

Case	h	Normal type		Low-leg type		B/L_i
	(mm)	d (mm)	d/h	d (mm)	d/h	
1	630	122	0.2	126	0.2	0.04
2						0.08
3						0.12
4						0.16
5	375	146	0.4	150	0.4	0.04
6						0.08
7						0.12
8						0.16
9	300	176	0.6	180	0.6	0.04
10						0.08
11						0.12
12						0.16
13	300	236	0.8	240	0.8	0.04
14						0.08
15						0.12
16						0.16

Table 2 Damage criteria

Damage form	
Turning	-
Sliding	Move more than 1/2 of the vertical and horizontal length of the block
Rotation or Subsidence	Subsidence and rotation due to unevenness more than 1/2 of the block thickness

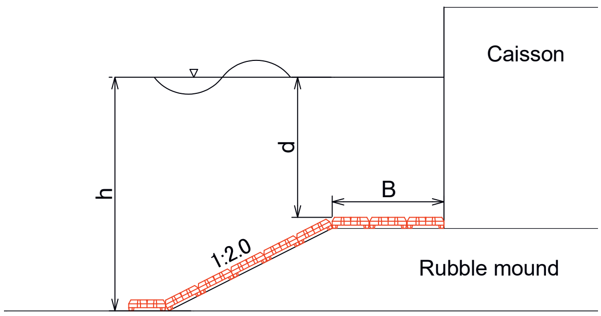


Fig.3 Cross-section of composite breakwater mound experiment model

2.2 Results of experiment

Figure 4 shows the experimental results of the low-leg type in the case of d/H =0.2; the vertical axis is Ns and the horizontal axis is B/L_i. The open symbols indicate the stable (no damage) test cases and the closed symbols indicate the damaged test cases. A solid line indicates a performance curve obtained by the critical Ns values of each B/L_i. Figure 5 shows the performance curves for the normal type and the low-leg type for the parameter of d/h. There was no significant difference between the leg types. The Ns increased as d/h increased in each B/L_i. Furthermore, the Ns increased as B/L_i increased for the same value of d/h. Figure 6 shows results of comparison to the performance curve of "STONE-BLOCK" which used generally as amour block. The performance curve of STONE-BLOCK was obtained by the experiment with regular waves conducted in 1980. The tendency of the performance curve is considered to be difference from that of random waves. Hence, the test cases of B/L_i=0.04, which the Ns of HONEY-CALM was lowest, was used for comparison. There was no significant difference for each Ns in the condition of d/h =0.6. On the other hand, the Ns of HONEY-CALM was higher than that of STONE-BLOCK in the condition of d/h =0.2. In general, when the wave height is the same, the uplift pressure in the condition of long wave period and low crown water depth is larger than that in the condition of the short wave period and deep crown water depth. Since HONEY-CALM has large apertures, it is considered that they effectively reduced the uplift pressure acted on HONEY-CALM.

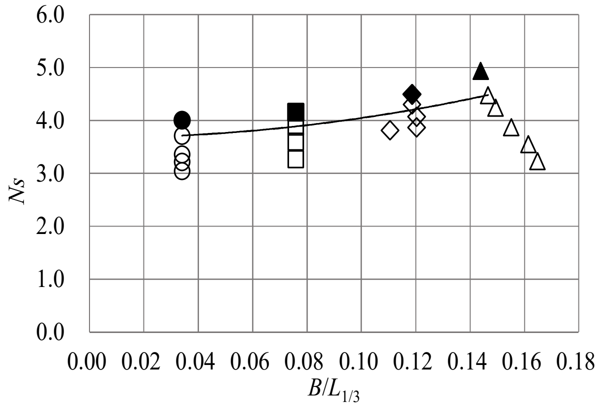
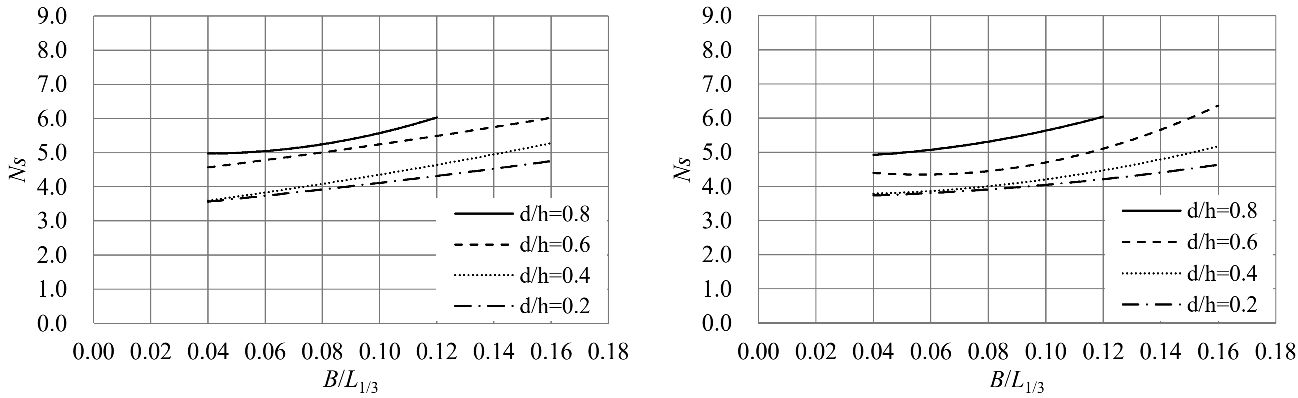
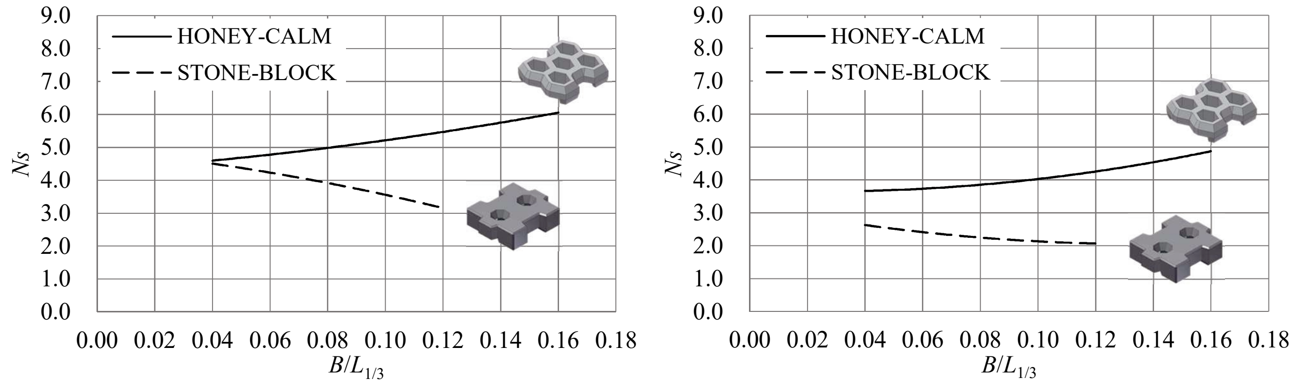


Fig.4 Experimental results of performance curve



a) Normal type b) Low-leg type

Fig.5 Performance curve of HONEY-CALM for the parameter of d/h



a) d/h=0.6 b) d/h=0.2

Fig.6 Comparison of block stability number Ns with STONE-BLOCK

Following Eqs. (2) ~ (5) are the empirical ones, obtained from experiments, to estimate Ns for each d/h in the case of the normal type block arranged vertical.

$$Ns = 161.04(B/L_i)^2 - 12.589(B/L_i) + 5.2199 \quad (d/H{=}0.8,\ 0.04{<}B/L_i{<}0.12) \tag{2}$$

$$Ns = 30.891(B/L_i)^2 - 5.9587(B/L_i) + 4.3104 \quad (d/H{=}0.6,\ 0.04{<}B/L_i{<}0.16) \tag{3}$$

$$Ns = 30.096(B/L_i)^2 - 6.2294(B/L_i) + 3.3126 \quad (d/H{=}0.4,\ 0.04{<}B/L_i{<}0.16) \tag{4}$$

$$Ns = 66.684(B/L_i)^2 - 3.3155(B/L_i) + 3.6891 \quad (d/H{=}0.2,\ 0.04{<}B/L_i{<}0.16) \tag{5}$$

3. COASTAL DIKE SLOPE

3.1 Overview of experiment

Experiments of a coastal dike slope were conducted using a wave flume of 50.0 m length, 1.0 m width and 1.5 m height. The coastal dike slope model was placed on a fixed bed with a foreshore slope of 1/30 in the flume. The crown had enough height not to occur wave overtopping. Figure 7 shows a cross-section of coastal dike slope model. The model scale was changed as 1/35 and 1/50. The weight of block model of normal type was 95.7 g and 32.9 g and the weight of low-leg type was 91.3 g and 31.3 g, for two scale models. The weight of prototype block is 4 t. Weights of rubble stones were between 100 kg to 500 kg in the prototype scale. Table 3 shows experimental conditions. The experimental wave periods were set to 10 s, 13 s, and 16 s in prototype, the installation arrangements were the vertical and horizontal. The slope gradients were 1:1.5 and 1:2.0. The experiment was conducted 40 cases changing block types, wave periods, installation arrangements and slope gradients. The incident wave was random waves with the modified Bretschneider-Mitsuyasu spectrum, and the acting wave number was 1,000. In each test, the wave height was increased several steps until block was damaged, and the critical wave height was examined. The definition of damage ratio was the same as before, that is, the ratio of damaged number to the total number. The block stability coefficient K_D was calculated using the Hudson's formula shown in Eq. (6). Where W is the block weight, ρ_c is the concrete density, $H_{1/3}$ is the significant wave height at the toe of breakwater, S_r is the ratio between concrete density and water density, and α is the angle between the coastal dike slope and the water surface.

$$M = \frac{\rho_c \times H_{1/3}^3}{K_D \times (S_r - 1)^3 \times \cot(\alpha)} \tag{6}$$

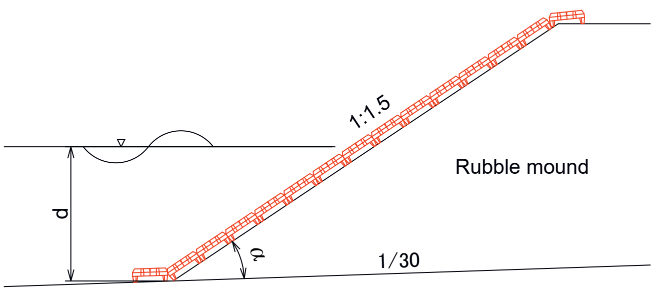


Fig.7 Cross-section of coastal dike slope experiment model

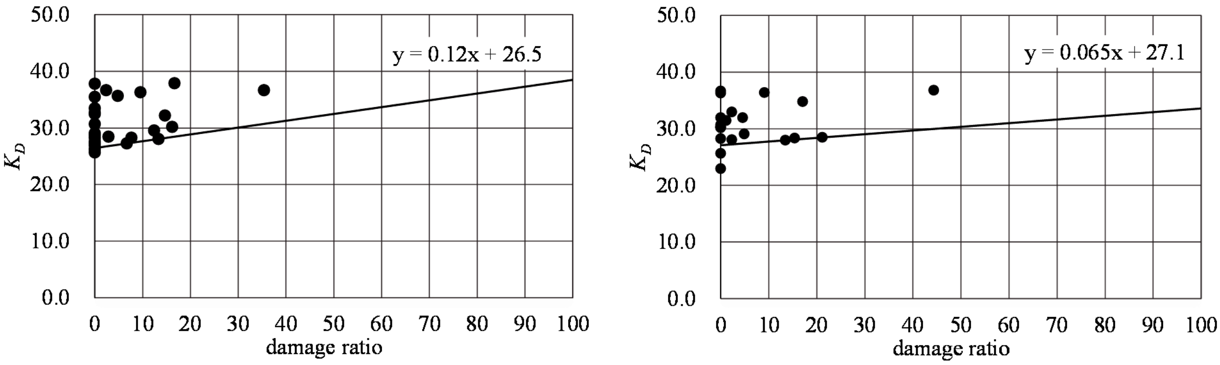
Table 3 Test cases for coastal dike slope experiment

case	Type	Installation direction	Scale	Slope gradient	Wave period (s)
1	Normal type and Low-leg type	Horizontal and Vertical	1/35 (4t)	1:1.5	10
2					13
3					16
4				1:2.0	10
5					13
6					16
7			1/50 (4t)	1:1.5	10
8					16
9				1:2.0	10
10					16

3.2 Results of experiment

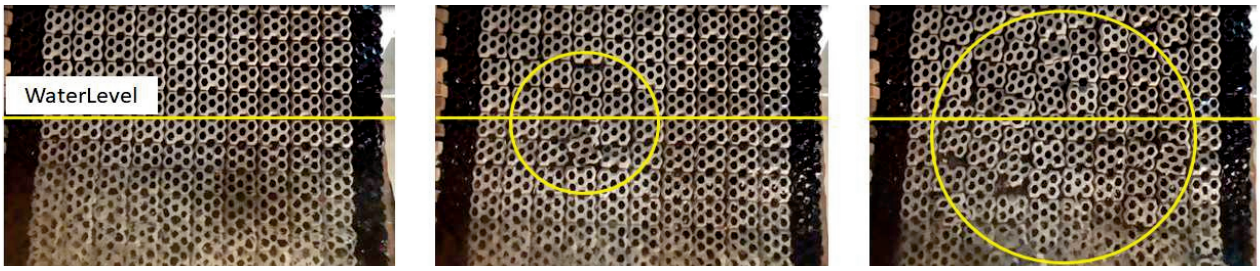
Figure 8 shows the relationship between K_D and the damage ratio for each of vertical and horizontal arrangement. The lowest K_D values among the damaged cases were represented by a straight line, and its intercept was adopted as K_D. The K_D values of the normal type block were estimated as 26.5 in the vertical arrangement and 27.1 in the horizontal arrangement, respectively. In the same way, K_D values of the low-leg type were estimated as 26.8 in the vertical arrangement and 27.5 in the horizontal arrangement. Summarizing the results, K_D value of HONEY-CALM was determined as 26.5 regardless of the block type and arrangement. The K_D value of STONE-BLOCK is from 10.0 to 10.6 under wave breaking condition, it was clarified that HONEY-CALM has K_D larger than twice that of STONE-BLOCK. The rubble stones did not flow out from apertures of HONEY-CALM. However, the rubble stones, near water surface, under HONEY-CALM were moved by the waves, and it caused ragged displacement of HONEY-CALM. As the waves continued to act, HONEY-CALM was damaged showing rotation and turning, and the damage spreads to surrounding blocks. Figure 9 shows an example of damage process. Such the damage form caused by rubble stones' movement occurred regardless of the block type and arrangement.

From these results, it is considered that the rubble stones under the block were susceptible to acted waves because HONEY-CALM has large apertures. Therefore, it is necessary to pay attention to damage caused by rubble stones movement when using HONEY-CALM in places where waves directly act on blocks used as coastal revetments.



a) Vertical arrangement b) Horizontal arrangement

Fig.8 Estimation of block stability coefficient K_D of HONEY-CALM



a) Experimental started b) Initial damage occurred c) Damage increased

Fig.9 Damage process of HONEY-CALM on coastal dike slope (Low-leg type)

4. ARTIFICIAL REEF

4.1 Overview of experiment

Artificial reef experiments were done in a wave flume, 30.0 m long, 0.7 m wide and 1.0 m high. A fixed bed with a slope of 1/30 was set in the flume bed, and an artificial reef model was set on it. Figure 10 shows a cross-section of artificial reef model. The slope gradient of artificial reef was set 1:3 on off-shore side and 1:2 on the

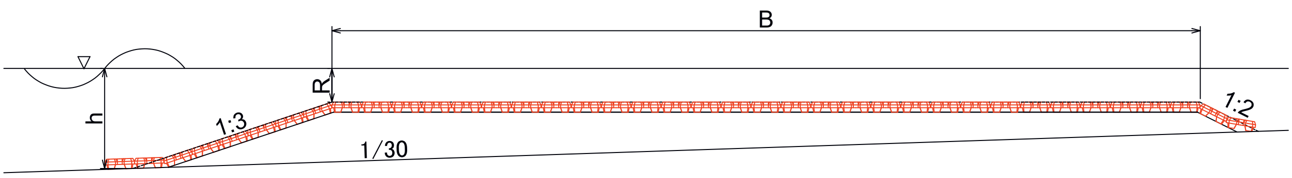


Fig.10 Cross-section of artificial reef experiment model

Table 4 Test cases for artificial reef experiment

case	crest depth (m)	Wave period (s)
1	0.00	10
2	0.00	13
3	0.00	16
4	1.00	10
5	1.50	13
6	1.50	16
7	2.00	10
8	3.00	13
9	3.00	16

shore side. The water depth h at the toe of reef was set 6.0 m, and the crest width B was set 50.0 m in the prototype scale. The crest water depth R was changed between 0 m to 3.0 m, and the wave period T was changed between 10 s to 16 s. Table 4 shows a list of experimental cases.

The model scale was 1/33.3 and the block weight was as follows: the normal type is 32.9 g and the low-leg type is 31.3 g, where the prototype block weight is 4 t. The installation arrangement was set the vertical arrangement. The incident wave was random waves with the modified Bretschneider-Mitsuyasu spectrum and the acting wave number was 1,000. The wave height was gradually increased until blocks were damaged. Damage ratio was calculated as the ratio, (the damaged number) / (the total number), and the allowable value of stability was set to 1%. The damage criteria were the same as that of composite breakwater test as Table 2. A block stability number Ns was calculated using a modified of the Brebner-Donnelly's formula shown by Eq. (7). Where M is the block weight, ρ_r is the block density, $H_{1/3}$ is the significant wave height at toe of breakwater, and S_r is the ratio of the density of concrete to seawater.

$$Ns = \frac{\rho_r^{1/3} \times H_{1/3}}{M^{1/3} \times (S_r - 1)} \tag{7}$$

4.2 Results of experiment

Figure 11 shows the relationship between Ns^3 and $R/H_{1/3}$ for $h/L_i = 0.047$ to 0.051. The closed circle indicates stable (no damage) cases outside of the surf-zone, the open circle indicates the stable cases in the surf-zone, and the x mark indicates the damage cases. Furthermore, the solid line indicates the performance curve connecting the maximum values of stable cases, and the dashed line and dotted line indicate the performance curves of STONE-BLOCK and a rectangular block (Suwa et al., 2016), respectively. In addition, all results plotted near the stability limit were within surf-zone. The performance curve for other ranges of h/L_i obtained similarly.
Eqs. (8) ~ (10) show the empirical equations of Ns for h/L_i. The range of h/L_i from 0.057 to 0.060 and from 0.078 to 0.080 with $R/H_{1/3} = 0.35$ or above is out of the valid range because the critical wave condition could not be obtained due to the limit of wave generator. The Ns^3 of HONEY-CALM in the case of $h/L_i = 0.047$ to 0.051 and $R/H_{1/3} = 0.0$ is about twice that of STONE-BLOCK. This indicates that the required amount of concrete can be reduced by 50%.
Figure 12 shows the relationship between K_t and B/L for each R/H_0' where K_t is the wave transmission coefficient. The open symbol indicates the result of HONEY-CALM and the closed symbol indicates the result of rectangular block (NILM). The K_t near $R/H_0' = 0.5$ of HONEY-CALM is about 6% lower for B/L=0.18 and about 35% lower for B/L=0.12 compared to the rectangular block case. Therefore, it was suggested that the longer the wave period, the higher the wave dissipating effect by HONEY-CALM.

$$Ns^3 = 30.948 e^{0.733 \times R/H_{1/3}} \quad (h/L_i = 0.047 \sim 0.051,\ 0.0 \leqq R/H_{1/3} < 0.55) \tag{8}$$

$$Ns^3 = 43.376 e^{0.878 \times R/H_{1/3}} \quad (h/L_i = 0.057 \sim 0.060,\ 0.0 \leqq R/H_{1/3} < 0.35) \tag{9}$$

$$Ns^3 = 59.284 e^{0.604 \times R/H_{1/3}} \quad (h/L_i = 0.078 \sim 0.080,\ 0.0 \leqq R/H_{1/3} < 0.35) \tag{10}$$

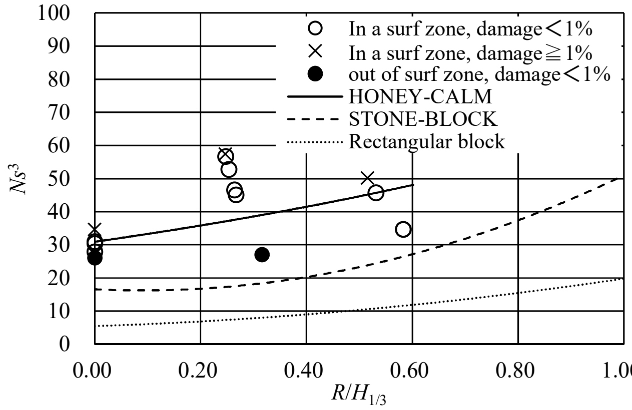


Fig.11 Experimental results of performance curve

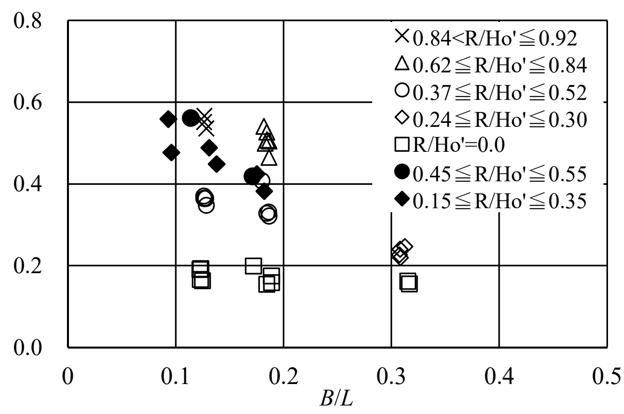


Fig.12 Wave transmission coefficient

5. TSUNAMI FLOW

5.1 Overview of experiment

Experiments of tsunami flow were conducted by an open channel. The size of the open channel is 30.0 m long, 0.7 m wide and 1.0 m high. A partition panel was installed at the center of the channel, and a caisson model was installed at one side of the channel. The other side was used as a return flow channel. A tsunami flow was reproduced by a steady flow generated by a submergible pump, which installed in the channel. Figure 13 shows overview of experimental channel, and Figure 14 shows an example of experimental cross-section. The raised rubble mound covered with HONEY-CALMs was installed behind the caisson model. Further, the caisson model was fixed to the channel wall avoid to be slid or overturned. The slope gradient of the raised rubble mound was set 1:2, and the crown width was set equal to the width of two armour blocks. The model scale was 1/50. The weights of block models were 95.7 g and 32.9 g of the normal-type, and 91.3 g and 31.3 g of the low-leg type, respectively. These weight in prototype are 4 t and 12 t. The block installation was the vertical arrangement and the horizontal arrangement. Table 5 shows a list of experimental cases. The tsunami flow was acted for 120 s (15 m in prototype) continuously. If the block did not move at the end of test, the tsunami flow was acted again with the increased flow depth with 1 cm. The critical stability number was determined by repetition of these operations until block was damaged. The relative damage level N_0 was calculated by Eq. (11), and the allowable value was defined by the value of 0.3 in which N is the damaged block number in the inspection area, B is the model installation width in the inspection area, D_n is the nominal diameter of the block. The damage criteria were the same as that of composite breakwater test as Table 2. The block stability number Ns was calculated using the formula of Mitsui et al. (2013) shown in equation (12). Where, h_1 is overflow depth, S_r is the ratio of the density of concrete to seawater, and D_n is representative diameter of a block.

$$N_0 = N / (B / D_n) \tag{11}$$

$$Ns = h_1 / (S_r - 1) D_n \tag{12}$$

5.2 Results of experiment

Figure 15 shows the relationship between Ns and d/H. The open circle indicates the test cases that critical stability and the closed circle indicates the test cases that the relative damage level more than 0.3. The solid line is the performance line that obtained by the least square method from distribution of the test cases, which becomes the critical stability condition. The dashed line indicates performance line of STONE-BLOCK. The Ns of HONEY-CALM was higher than that of STONE-BLOCK in the all condition. It is considered that HONEY-CALM reduced uplift pressure from seepage and overflow by the apertures of blocks. In other cases, performance curves were obtained in the same way.

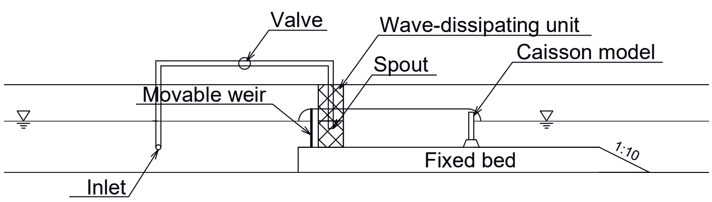


Fig.13 Experimental channel overview

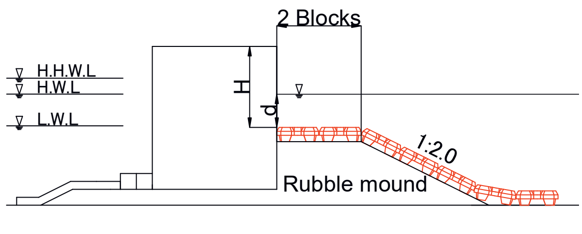


Fig.14 Cross-section of tsunami overflow experiment model

Table 5 Test cases of tsunami overflow experiment

case	Type	Installation arangement	Weight	Watar Level
1	Normal type and Low-leg type	Horizontal and Vertical	4t	H.H.W.L
2				H.W.L
3				L.W.L
4			12t	H.W.L
5				L.W.L

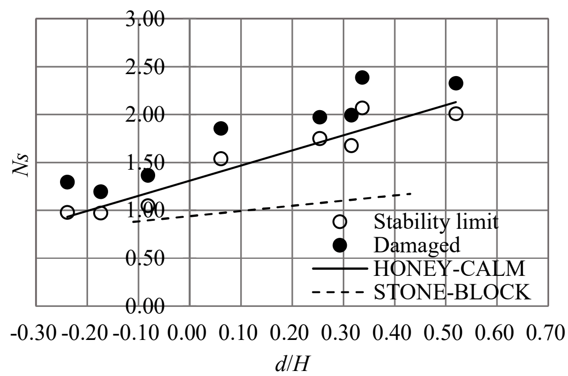


Fig.15 Performance line of HONEY-CALM

Empirical equations were derived as Eqs. (13) ~ (16), obtained from the performance. These equations are valid in each range of d/H where stability has been confirmed in the experiments. The Ns of horizontal arrangement was higher than that of the vertical arrangement in both the normal type and the low-leg type. The tsunami flow at horizontal arrangement passed over the raised rubble mound crown easily because the crown width of the horizontal arrangement is smaller than the vertical arrangement. Therefore, HONEY-CALM placed on crown with the horizontal arrangement was more influenced by tsunami overflow than that of vertical arrangement.

Normal type, Vertical arrangement $Ns = 1.5835(d / H) + 1.3083$ $(-0.24 \leqq d/H < 0.52)$ (13)

Normal type, Horizontal arrangement $Ns = 1.4693(d / H) + 1.3857$ $(-0.24 \leqq d/H < 0.51)$ (14)

Low-leg type, Vertical arrangement $Ns = 1.3885(d / H) + 1.1762$ $(-0.21 \leqq d/H < 0.52)$ (15)

Low-leg type, Horizontal arrangement $Ns = 1.4921(d / H) + 1.2773$ $(-0.20 \leqq d/H < 0.52)$ (16)

6. CONCLUSIONS

This study examined the stability performance of HONEY-CALM, applied to various coastal structures, against wind waves and tsunamis by a series of hydraulic model experiments. The main results are summarized as follows.

1. In composite breakwater experiments, the stability number Ns of HONEY-CALM newly developed is higher than STONE-BLOCK commonly used. Especially, it is remarkable when the condition of the long wave period and low crown depth. It is considered that the apertures effectively reduced the uplift pressure acted on HONEY-CALM.
2. In coastal dike slope experiments, the stability number K_D of HONEY-CALM was almost constant of 26.5. Although the rubble stones did not flow out of from apertures of HONEY-CALM, the rubble stones under HONEY-CALM, near water surface, were moved by the waves. Therefore, it is necessary to pay attention to damage caused by rubble stones move when using HONEY-CALM in places where waves directly act on blocks such as coastal revetments.
3. In artificial reef experiments, the Ns of HONEY-CALM was up to about twice as high as STONE-BLOCK. In addition, the wave transmission coefficient was lower than that of STONE-BLOCK especially when the condition of the long wave period. It is suggested that the longer the wave period, the higher the wave dissipating effect of HONEY-CALM.
4. In tsunami flow experiments, the Ns of HONEY-CALM was higher than that of STONE-BLOCK in the all condition. It is considered that HONEY-CALM reduced uplift pressure from seepage and tsunami flow by the apertures. The Ns of horizontal arrangement was higher than the vertical arrangement in both the normal type and the low-leg type. The tsunami flow at horizontal arrangement was pass over the raised rubble mound crown easily because the crown width of the horizontal arrangement is smaller than the vertical arrangement.

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