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Influences of Global Warming on Wave Dissipating Blocks

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Abstract: As the air and seawater temperatures rise due to global warming, sea conditions are becoming increasingly severe. It is concerned that severe sea conditions will damage wave dissipating blocks installed at the front face of breakwaters and coastal revetments. When the wave dissipating blocks are damaged, hydraulic performance such as the reductions of the reflected waves, the transmitted waves and the wave pressure acting on the caisson are declined. When maintaining and managing breakwaters, reinforcement of wave dissipating blocks is necessary, but currently, the change in hydraulic performance is not accounted for in determining the need for reinforcement. The authors have examined the stability of the blocks by conducting hydraulic model experiments considering the change in sea conditions due to climate change. Moreover, deterioration in the hydraulic performance of the blocks due to the deformation of the blocks is examined by numerical simulation. The evaluation of the change of the hydraulic performance is proposed to apply to the judgment of the necessity of reinforcement of the blocks.

Keywords: Global warming, Wave dissipating blocks, Hydraulic performance, Hydraulic model experiment, Numerical simulation

1 Introduction

Wave dissipating blocks are installed in front of the caissons of a composite breakwater to improve its stability, and to reduce the heights of the transmitted and the reflected waves. Similarly, the blocks are installed in front of coastal revetments to reduce the wave overtopping over the revetments and the height of the reflected waves. To maintain the stability of breakwaters and coastal revetments, it is important to keep the hydraulic performance of the blocks.

Owing to the increasing air temperature and seawater temperature associated with steadily advancing global warming, there has been an increase in the number of strong hurricanes and typhoons, and the following changes have occurred in sea conditions: Increases in wind speed, increases in sea level deviation in a storm surge, increases in wave height, and increases in sea level. Changes in these sea conditions lead to a decrease in the stability of wave dissipating blocks. Therefore, it is likely that the wave dissipating blocks, which have been stable until now, will suffer from these changes. The deformation of the wave dissipating blocks causes the following changes in their hydraulic performance: Deterioration of the stability of the wave dissipating blocks, decreased stability of the caisson, increase in the wave overtopping, increase in the transmitted wave height, and increase in the reflected wave height.

The number of breakwaters more than a few decades old is increasing in Japan. For example, the percentage of breakwaters over 50 years since construction is currently 10 %, reaching about 60 % after 20 years. Hence, wave dissipating blocks need to be reinforced from the viewpoints of maintenance and management. However, currently there is no clear criterion for the necessity of these reinforcements. Even if the changes in the hydraulic performance are slight, the reinforcement of the wave dissipating blocks have been performed. Therefore, it is desirable to clarify the relation between the deformation of the wave dissipating blocks and the deterioration of hydraulic performance as a judgment index for the necessity of reinforcement the wave dissipating blocks.

By considering the above situations, the deformation of the wave dissipating blocks due to the sea condition changes and deterioration of hydraulic performance are examined by hydraulic model experiment and numerical simulation.

2 Deformation of wave dissipating blocks due to changes in sea conditions

Numerical simulation is becoming possible to study the stability of structures. However, at present, hydraulic model experiments are more suitable than numerical simulations to take into account the differences in the shape of the blocks for evaluating stability. Therefore, the deformation of the wave dissipating blocks owing to changes in sea conditions has been examined by in the hydraulic model.

2.1 Typical breakwater structure types

The composite breakwater, of which the front surface is covered with wave dissipating blocks are often adopted in Japan. Fig. 1 shows a typical structure types of composite breakwater. Rectangular caisson breakwater is adopted most widely in Japan. The crest freeboard of the rectangular caisson, R_c, is normally 0.6 times high as the design significant wave height, H_s, above the high water level. Usually the armour freeboard of wave dissipating blocks, A_c, is the same as the R_c in rectangular caisson breakwater. Therefore, A_c/H_s is 0.6. Due to these freeboards R_c and A_c, the transmitted wave height is approximately 0.2 times the incident significant wave height. According to the recent port size increases, breakwaters should be constructed in the offshore deeper area. However, in such an offshore area, the size of the breakwater becomes large and the construction cost is more expensive. To address this problem, a breakwater with sloping top structure is adopted, as shown in Fig. 1. In the sloping top caisson breakwater, the width of the caisson can be reduced by the effect of pressing the caisson downward generated by the wave force acting on the upper slope portion. Moreover, since wave dissipating blocks are not necessary to install in the upper slope portion, the armour freeboard of the blocks, A_c, can be lowered. Thus, sloping top caisson breakwaters have lower construction costs than rectangular caisson breakwaters. However, to make the transmitted wave height approximately 0.2 times high as the incident significant wave height, it is necessary to make the crest freeboard, R_c, approximately 1.0 times high as the design significant wave height above the high water level comparing to 0.6 times high for the rectangular caisson breakwater.

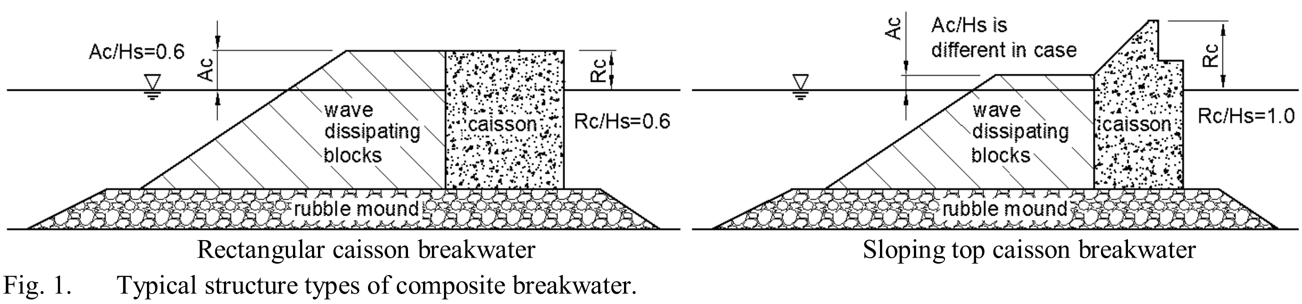

Fig. 1. Typical structure types of composite breakwater.

Tab. 1. Size of experimental facilities

	length	width	depth
wave flume 1	50.0 m	1.0 m	1.5 m
wave flume 2	38.0 m	1.0 m	1.5 m
wave flume 3	105.0 m	0.8 m	2.5 m
wave basin	56.0 m	42.0 m	1.0 m

2.2 Verification conditions of the stability of the wave dissipating blocks through hydraulic model experiment

The deformation of the wave dissipating blocks in front of the caisson of the composite breakwater has been examined by changing the sea condition in the hydraulic model. The hydraulic model experiments on stability were carried out with three different wave flumes and one wave basin. Tab. 1 lists the size of the experimental facilities where the hydraulic model experiments have been conducted. Fig. 2 shows the longitudinal cross section of Experiment 1. In the wave flumes, the experiments have been conducted by changing the structural type of the breakwater and the type and size of the blocks. In the wave basin, the experiments have been carried out by changing the size of the blocks and the angle of wave incidence. Tab. 2 lists the typical experimental conditions. Fig. 3 shows the shape of the blocks.

Tab. 2. Typical experimental conditions

experiment series	experimental facility	breakwater structure type	wave dissipating block				angle of wave incidence
			shape	Dn (cm)	mass density	mass (gf)	
Experiment 1	wave flume 1	sloping top caisson	Block 1	7.02	2.3	796	0 °
			Block 2	7.47	2.3	959	
Experiment 2	wave flume 2	rectangular caisson	Block 3	5.43	2.3	368	0 °
				5.89	2.3	471	
				6.54	2.3	644	
Experiment 3	wave flume 2	sloping top caisson	Block 3	5.43	2.5	400	0 °
				5.89	2.3	471	
Experiment 4	wave flume 3	rectangular caisson	Block 3	6.54	2.55	714	0 °
			Block 4	5.58	2.36	411	
Experiment 5	wave basin	rectangular caisson	Block 3	3.69	2.3	116	0° ,22.5° ,45°
				4.00	2.3	147	

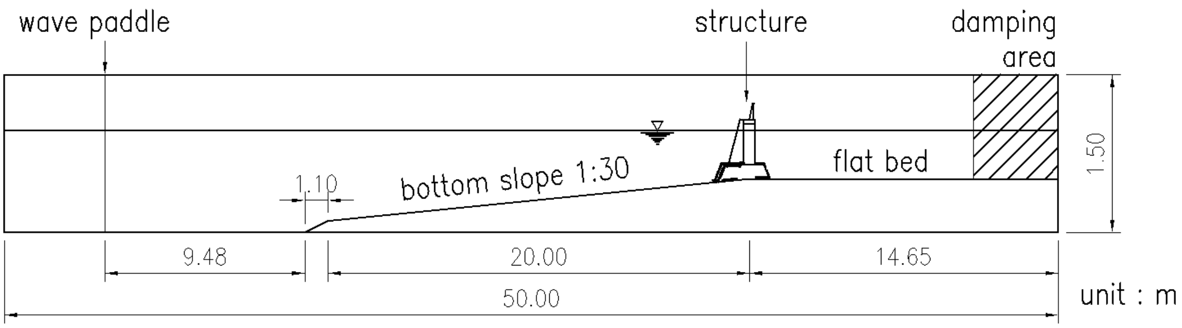

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Fig. 2. Longitudinal cross section of experiment 1.

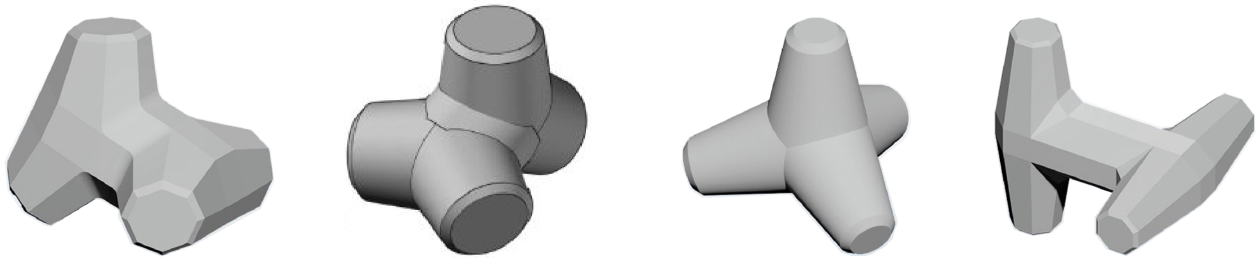
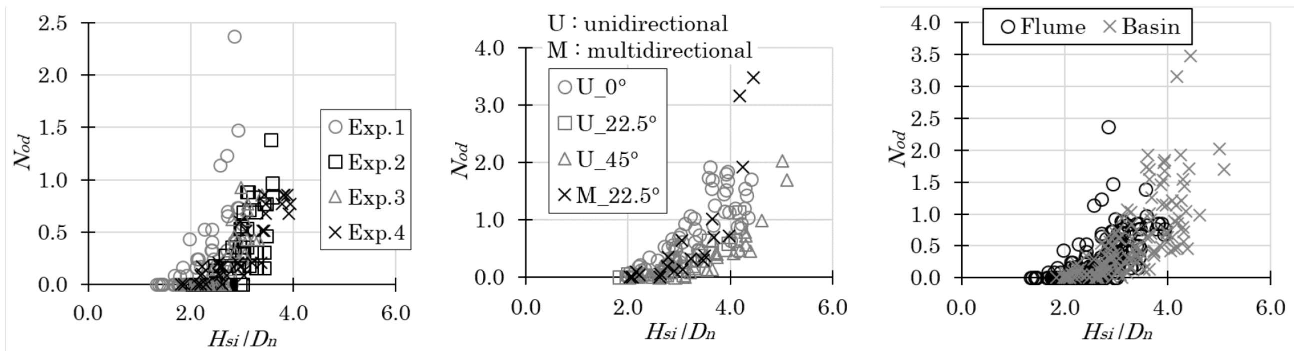


Fig. 3. Shape of wave dissipating blocks.

2.3 *Verification result of the stability of wave dissipating blocks by hydraulic model experiments*

2.3.1 *Stability of wave dissipating blocks with wave height increase*

Fig. 4 shows the results of hydraulic model experiments on the relation between the significant wave height and damage of the wave dissipating blocks: where H_{si} is the incident significant wave height at the breakwater installation position, D_n is the nominal cube length of block, i.e. the length of a cube with the same volume of as that of a block, and N_{od} is the number of displaced units within a 1 D_n. The start of the damage is the dislodged of the first block, and the acceptable N_{od} is usually 0.3. Hence, N_{od} over 0.3 is failure. The N_{od} of 0.3 is almost equal to the damage percentage N_d of 1 %. The damage percentage is defined as the percentage of dislodged blocks to the total number of blocks. Fig. 4 (1) shows the results of Experiment 1 to Experiment 4, which were carried out in the wave flumes. The scatter is a little large. Because of the damage of sloping top caisson is greater than the damage of rectangular caisson. Fig. 4 (2) shows the results of Experiment 5, which was carried out in the wave basin. The scatter is a little large. The reason is that the degree of damage differs depending on the angle of wave incidence. Fig. 4 (3) summarizes the experimental results of the wave flumes and those of the wave basin, and it can be seen that the results of flumes and basin are almost the same.



(1) Experiments 1 to 4 (Wave Flumes)
(2) Experiment 5 (Wave Basin)
(3) Experiments 1 to 5 (Wave Flumes and Wave Basin)

Fig. 4. Relation between the wave height and the damage number N_{od} of the wave dissipating blocks.

When the wave height increases, the damage of the wave dissipating blocks increase as shown in Fig. 4. Therefore, if the wave height exceeds the design wave height due to changes in sea conditions, it is feared that the wave dissipating blocks will be damaged. As the wave height increases, the damage to the wave dissipating blocks naturally increase. However, if the increase in the wave height is within the stability margin of the wave dissipating blocks, the increase in wave height may not affect the stability of the wave dissipating blocks. For example, in the case that the required mass of a block, estimated by stability formula, is 42 tonne, a 50-tonne block is employed, because of the 40-tonne block is insufficient. In this case, the 50-tonne block has a margin of 8 tonne in mass, even if the wave height increases within this margin, the stability of the wave dissipating blocks may not be significantly affected.

2.3.2 Stability of wave dissipating blocks against sea level rise

If the sea level rise and sea level deviation in storm surge increase due to the climate change, higher waves will act in a higher sea level than before. In general, the wave dissipating blocks tend to be damaged when their freeboard is lower as compared to the case where the freeboard is high.

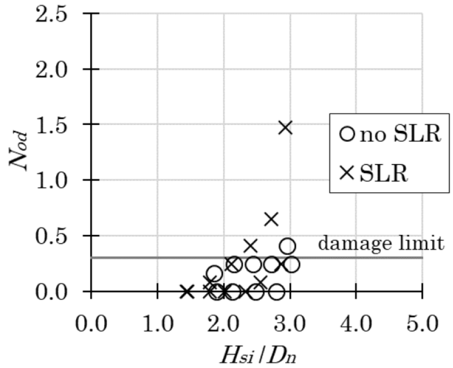


Fig. 5. Comparison of N_{od} value in the cases of no sea level rise and sea level rise (SLR).

Fig. 5 shows a comparison of N_{od} of the wave dissipating blocks in the cases of no sea level rise and sea level rise (hereinafter referred to 'SLR'). It is the result of Experiment 1 listed in Tab. 2. The amount of SLR is 0.6 times D_n. The value of N_{od} with SLR is greater than that of no SLR. Therefore, if the rise of sea level and sea level deviation in a storm surge increase due to climate change, the wave dissipating blocks will be easily damaged. When H_{si}/D_n is less than 2.0, the value of N_{od} is almost the same no SLR and SLR, but when H_{si}/D_n exceeds 2.0, the N_{od} value with SLR is larger than that no SLR. From this, it can be said that the influence that a rise in sea level gives to the stability of the wave dissipating blocks appears remarkably under the condition of a large wave height. If the sea level rise is larger than 0.6 times D_n, the rise in water level may affect the stability of the wave dissipating blocks even if H_{si}/D_n is smaller than 2.0.

2.3.3 Stability of wave dissipating blocks with wave duration

Due to the climate change, the duration of high waves may be extended. Therefore, we have examined the stability of the blocks by increasing the number of waves at the same wave height.

Fig. 6 shows the relation between the number of waves, N, and N_{od} value. It is the result of Experiment 5 listed in Tab. 2. The wave height is increased stepwise up to 5000 waves. The wave height is 0.61 times of the design wave height in wave numbers 1 to1000, the wave height is 0.77 times of the design wave height in wave numbers 1001 to 2000, the wave height is 0.89 times of the design wave height in wave numbers 2001 to 3000, the wave height is the design wave height in wave numbers 3001 to 4000, the wave height is 1.18 times of the design wave height in wave numbers 4001 to 5000. Wave numbers 5001 to 6000 and 6001 to 7000 are also 1.18 times of the design wave height. Therefore, the results in the wave numbers from 4001 to 7000 are useful to evaluate the progression of damage for every 1000 waves under the constant wave height.

As the wave height is increased every 1000 waves from the wave numbers of 1 to 5000, the N_{od} value is increased. The wave numbers from 4001 to 7000 is the same wave height, but N_{od} value increases with the wave number. That is, if the wave height larger than the design wave height acts for a long duration, the damage to the wave dissipating blocks progresses. However, compared to the increase rate in N_{od} value from 4001 to 5000 in the wave number, the increase rate of N_{od} value is slightly slower after 5001. The reason is the poor engagement blocks displaced in the early stage, and the remaining blocks have higher resistance. Kubota et al. (2003) reported that the tightening resistance of the wave dissipating blocks increases with the tightening of the wave dissipating blocks.

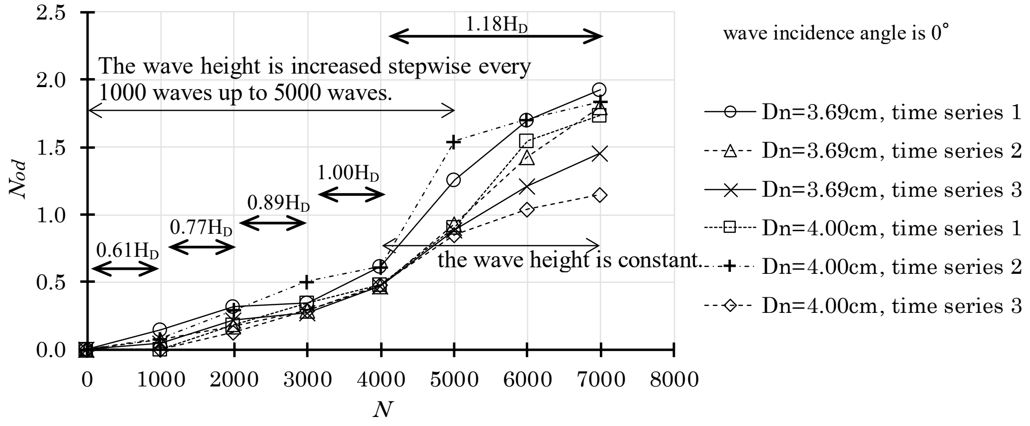


Fig. 6. Increase in damage to wave dissipating blocks due to increases in wave height and number of waves.

2.3.4 Stability of wave dissipating blocks with angle of wave incidence

The wave direction changes with the passing of hurricanes and typhoons. Therefore, the angles of the waves acting on the breakwater changes with time. Changes in the angles of wave incidence are not related to climate change, but the influence of the angles of wave incidence is important in evaluating the stability of the wave dissipating blocks. It has been examined not enough that the influence of the angles of wave incidence inflict to the stability of wave dissipating blocks. Therefore, we have examined the influence of the angles of wave incidence.

Fig. 7 shows a comparison between N_{od} value and H_{si}/D_n by distinguishing the angles of wave incidence. It is the result of Experiment 5 listed in Tab. 2. The N_{od} value at 0°, where waves act in a direction perpendicular to the breakwater, is large, and decreases as the inclination of the wave action angle increases. Therefore, if the stability of the blocks are examined by the hydraulic model experiment of the wave flume implemented at perpendicular incidence, the damage will be overestimated.

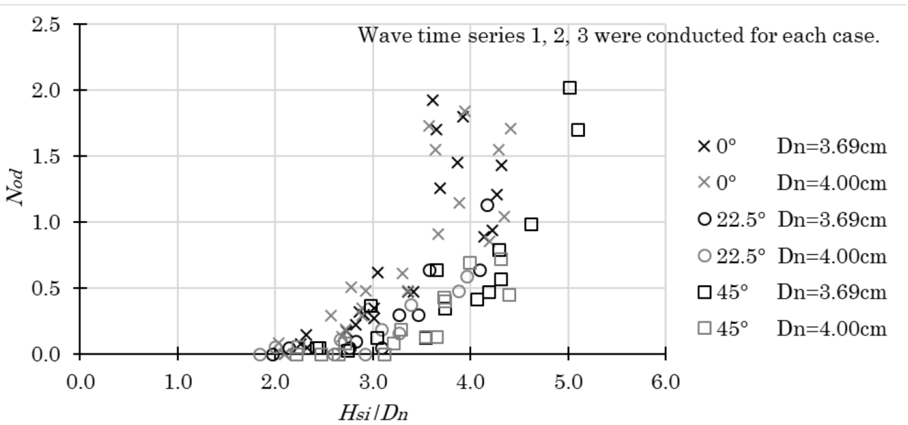


Fig. 7. Relation between N_{od} value and H_{si}/D_n due to difference in angles of wave incidence.

3 Changes in hydraulic performance by deformation of wave dissipating blocks

The wave dissipating blocks covering the front of breakwaters and coastal revetments have hydraulic performance of reducing several phenomena such as reflected waves, transmitted waves, the wave overtopping, and the wave power acting on the caisson. We have carried out numerical simulations on the changes of hydraulic performance in the state where the deformation of the wave dissipating blocks induced by wave height increase and sea level rise. The numerical simulation model applied to the examination is CADMAS-SURF (eg. Isobe et al., 1999) based on the VOF method. Ota et al. (2007), Kashima et al. (1992), Seki et al. (2009), Kubota et al. (2017) reported the following: "The greater the deformation of the wave dissipating blocks is, the greater the wave overtopping rate is" "The greater the deformation of the wave dissipating blocks is, the lower the reflection coefficient is due to the increase in the wave overtopping rate". and "The wave force acting on the caisson becomes larger as the freeboard of the wave dissipating blocks get lower."

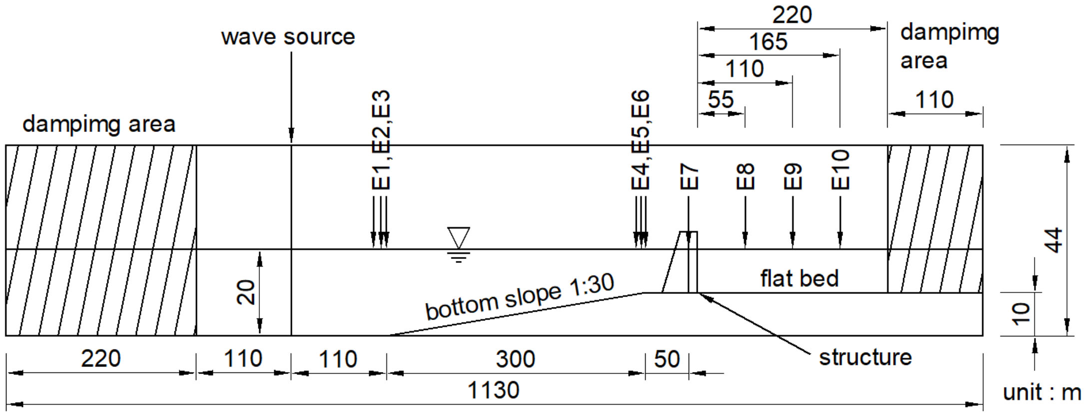


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Fig. 8. Computational domain of numerical simulation to evaluate hydraulic performance.

3.1 Verification condition of hydraulic performance of wave dissipating blocks by numerical simulation

Fig. 8 shows the calculation area of the numerical simulation for evaluating the hydraulic performance. The water depth at the wave source position is 20 m. The waves used in this study are irregular waves and the periods of significant waves T_s are 6.0 s and 12.0 s respectively. The distance from the wave source to the start of the bottom slope is 110 m, which is twice the wavelength of period of 6.0 s. Because the wavelength of the water depth at 20 m and period of 12.0 s is 152 m, a distance of 110 m from the wave source to the start of the bottom slope is 72 % of the 12.0 s wavelength. The seabed slope is 1/30 and the water depth at the breakwater installation site is 10 m. The installation position of the structure is 50 m from the sea side end of the flat bed. Positions of E1 to E10 are time series output points of the water surface elevation. Positions of E1 to E3 and E4 to E6 in front of the breakwater are used to calculate the separation of incident and reflected waves by the two gauges method proposed by Goda and Suzuki (1976). The combination of E2 and E3 and the combination of E5 and E6 are used for the separation of waves of 6.0 s. Also, the combination of E1 and E3 and the combination of E4 and E6 are used for the separation of waves of 12.0 s.

The distance between the water surface elevation output points for separation analysis of the incident and reflected waves is about 1/10 of the wavelength. Position of E7 is located in front of the breakwater. Position of E8 to E10 are output points of time series of the water surface elevation of the transmitted wave. The positions of E8 to E10 were 0.5, 1.0, and 1.5 times the wavelength of the incident wave from the back of the caisson. The wavelength of incident wave of 12.0 s in period is 113 m at the depth of 10 m.

3.2 Verification result of hydraulic performance of wave dissipating blocks by numerical simulation

3.2.1 Changes in hydraulic performance due to decrease in the crest width of wave dissipating blocks

Fig. 9 shows the breakwater cross sections of the calculation for evaluating the change in hydraulic performance due to the reduction of the crest width of the wave dissipating blocks, G_c. The rubble mound is omitted and a caisson and the wave dissipating blocks are set on the flat bed. The design wave period is 12.0 s and the design significant wave height is 6.95 m at the breakwater installation position. The crest freeboard of the caisson, R_c, and armour freeboard, A_c, is 4.0 m, which is about 0.6 times the design significant wave height.

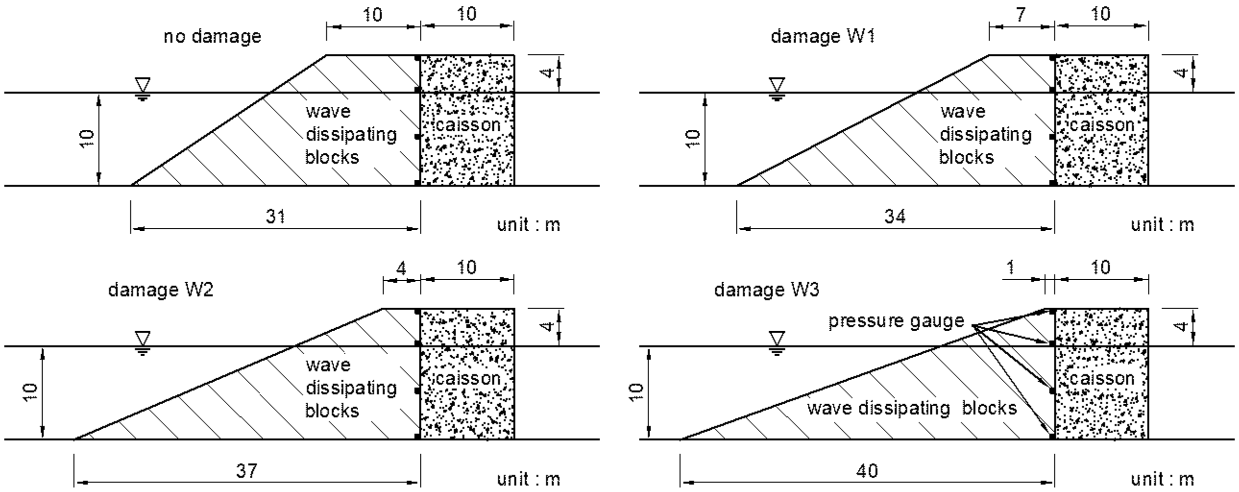
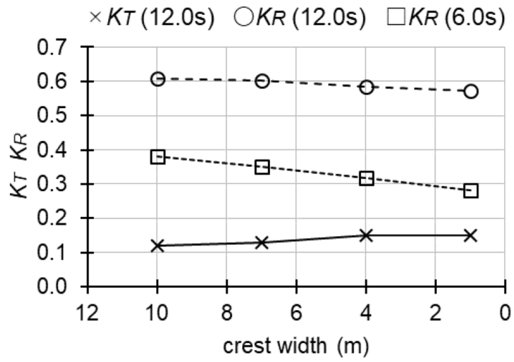


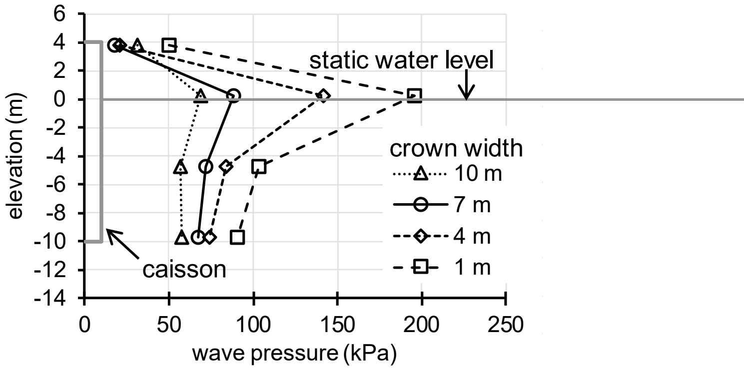
Fig. 9. Breakwater cross section of calculation to evaluate change in hydraulic performance due to reduction in crest width of wave dissipating blocks.

The crest width of no damage is set to 10 m, which is a standard crest width of the block of the required mass against for the design significant wave height. Damage W1 to damage W3 have a shape that assumes a state in which the crest width is reduced due to the damage caused to the blocks. These profiles from damage W1 to damage W3 are not the actual profiles, but simplify profiles for evaluating changes in hydraulic performance caused by reduce of crest width. The crest width of the blocks is reduced by 3.0 m at a time for damage W1 to damage W3. The cross-sectional area of the blocks is kept constant by increasing the bottom width of the blocks. Besides the time series of water surface elevation, the time series of the wave pressure has been output at four points on front of the caisson shown in damage W3 of the figure. Waves with incident significant wave height H_{si} of 5.08 m at a depth of 20 m and a period of 12.0 s are applied to the cross section of the breakwater in Fig. 9 to analyze the wave transmission coefficient, reflection coefficient and wave pressure acting on the caisson. In addition, the reflection coefficient is analyzed by applying a wave with H_{si} of 0.99 m at a depth of 20 m and a period of 6.0 s.

Fig. 10 shows the calculation results. The wave transmission coefficient K_T increases as the crest width of the wave dissipating blocks, G_c, narrows. However, the wave transmission coefficient K_T is 0.12 at a crest width of 10 m is about 0.15 at a crest width of 1 m, and the change in the wave transmission coefficient K_T due to the reduction in the crest width is not very large. If the crest width of the wave dissipating blocks is reduced, the reflection coefficient K_R with the period of 6.0 s decreases. As the wave height is as small as 0.99 m, waves do not reach the crest of the wave dissipating blocks with the period of 6.0 s. Therefore, it is considered that the reflection coefficient K_R is reduced due to the effect that the wave dissipating blocks cross section under the water surface is increased as much as the crest width of the wave dissipating blocks is decreased. If the wave dissipating blocks crest width is made smaller, the reflection coefficient K_R with the period of 12.0 s becomes smaller. However, the decrease in reflection coefficient K_R with the period of 12.0 s is less than that with the period of 6.0 s. Because the wave height is large in the period of 12.0 s, the wave reaches higher than the crest of the wave dissipating blocks. Therefore, the reflection coefficient is slightly reduced because the wave overtopping increases as the crest width decreases. The wave pressure acting on the caisson is greatly increased as the crest width of the wave dissipating blocks is reduced. In the range where the reduction in the crest width is small, the increase in wave pressure at the static water level is small, but when the reduction of the crest width becomes large, the wave pressure at the static water level becomes extremely large. The wave pressure with a crest width of 1 m at the static water level exceeds 2.8 times the crest width of 10 m. In the change of hydraulic performance due to the reduction of the crest width of the wave dissipating blocks, the change of the transmission wave height and the reflected wave height are small but the increase of the wave pressure acting on the caisson is large.



wave transmission coefficient and reflection coefficient



wave pressure acting on the caisson

Fig. 10. Changes in hydraulic performance due to the reduction in crest width of wave dissipating blocks.

3.2.2 Change in hydraulic performance due to reduction in the crest height of wave dissipating blocks

Fig. 11 shows the breakwater cross section of the calculation of change in the hydraulic performance due to reduction in the crest height of the wave dissipating blocks. The cross section of no damage is the same cross section as the no damage in Fig. 9. In damage H1 to H3, the crest height is lowered by 3.5 m and the crest width of the wave dissipating blocks is increased so that its area is almost the same as the case of no damage. These profiles from damage H1 to damage H3 are not the actual profiles, but simplify profiles for evaluating changes in hydraulic performance caused by reduction of crest height. The period of significant wave T_s is 12.0 s, and the incident significant wave height H_{si} is 5.08 m of water depth at 20 m.

Fig. 12 shows the calculation results. The wave transmission coefficient K_T increases as the crest height of the wave dissipating blocks decreases. The wave transmission coefficient K_T with a crest height of +0.5 m, which is 3.5 m lower than the crest height of the caisson, reaches 0.18. It is larger than the wave transmission coefficient with a crest width of 1 m in the Fig. 10. The reflection coefficient K_R decreases at the crest height decreasing from +4.0 m to -3.0 m, but increases at -6.5 m. The effect of the wide wave dissipating structure at the crest is obtained up to -3.0 m, but when the crest height is lowered to -6.5 m, the water depth becomes too large to obtain the wave dissipating effect. The wave pressure acting on the caisson increases as the crest height of the wave dissipating blocks decreases. The increase in wave pressure when the crest height of the wave dissipating blocks is 3.5 m lower is larger than when the crest width is 3.0 m smaller in the Fig. 10.

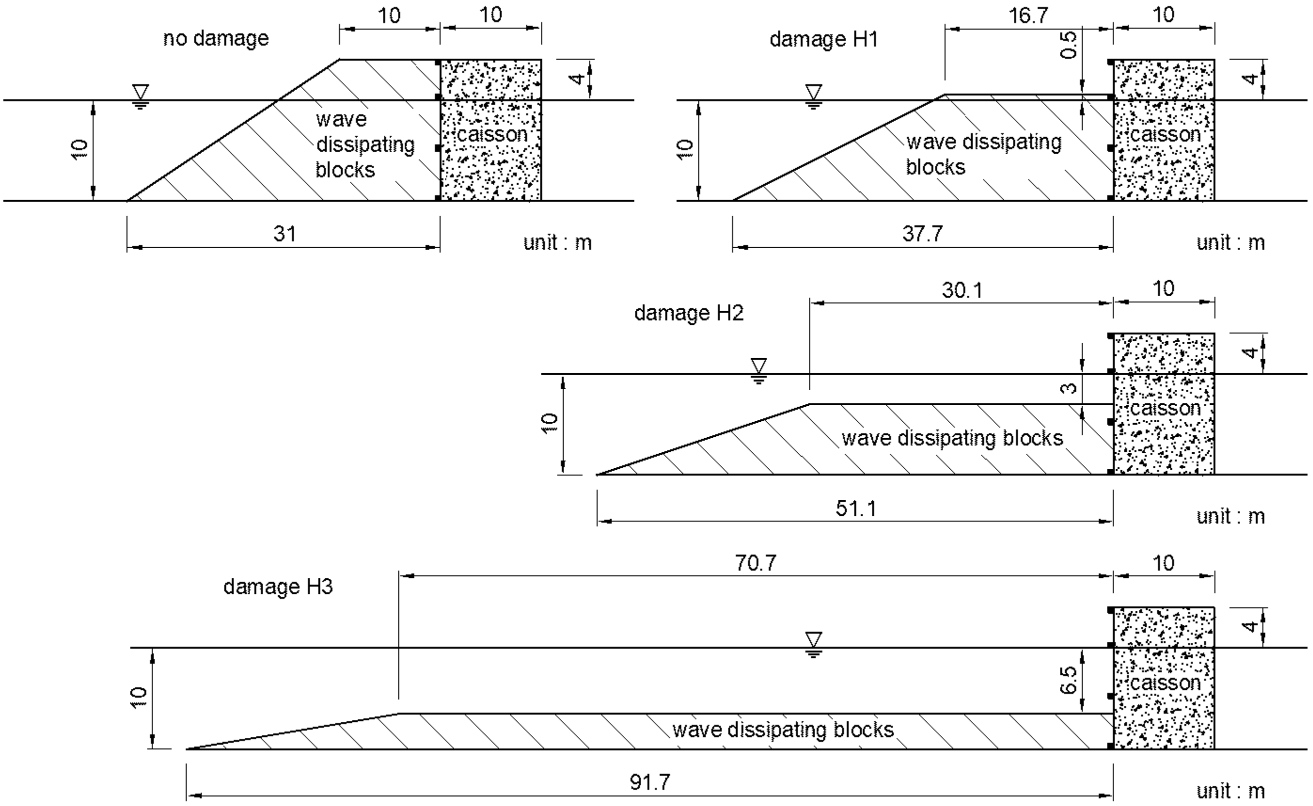
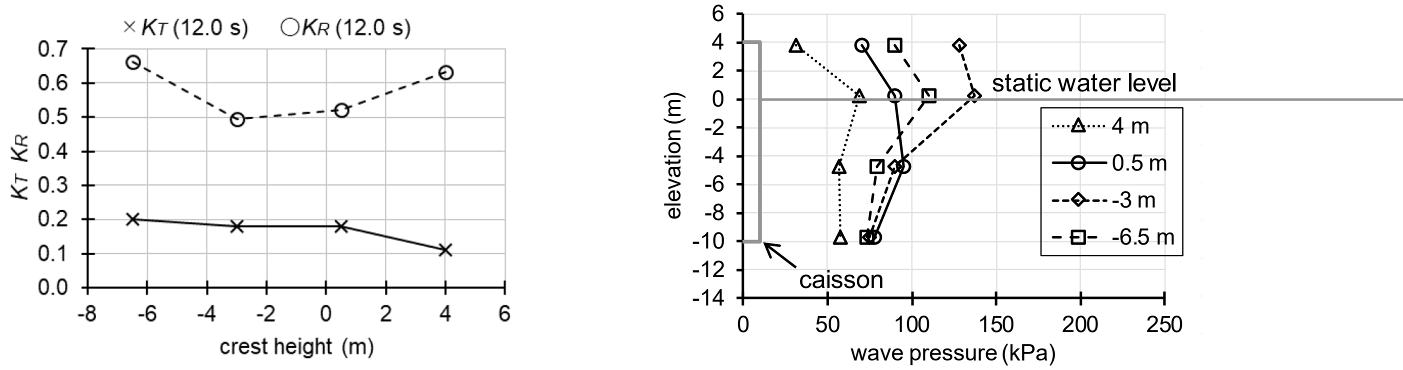


Fig. 11. Breakwater cross section of calculation to evaluate change of hydraulic performance due to reduction of crest height of wave dissipating blocks



wave transmission coefficient and reflection coefficient

wave pressure acting on the caisson

Fig. 12. Change in hydraulic performance by reduction in the crest height of wave dissipating blocks

3.3 Utilization of hydraulic performance evaluation

The relation between the deformation of the wave dissipating blocks and the change in the hydraulic performance has been confirmed. The increase in the wave transmission coefficient due to the decrease in the crest width of the wave dissipating blocks is not very large, and the reflection coefficient is somewhat small. However, the wave pressure acting on the caisson is greatly increased when the amount of reduction in the crest width is large. As the crest height of the wave dissipating blocks decreases, the wave transmission coefficient, as well as the wave pressure acting on the caisson, increases. The change in the hydraulic performance due to the reduction in the crest height of the wave dissipating blocks is larger than the reduction in the crest width of the wave dissipating blocks.

It changes according to the deformation of the wave dissipating blocks that the hydraulic performance of reducing several phenomena such as reflected waves, transmitted waves, the wave overtopping, and the wave force acting on the caisson. However, if the deformation is small, the decrease in hydraulic performance is small. Therefore, unnecessary reinforcement of the wave dissipating blocks can be avoided or reinforcement can be performed at an appropriate time by utilizing the evaluation of the change in hydraulic performance of the wave dissipating blocks.

4 Conclusions

Climate change due to global warming causes changes in sea conditions such as wave height increase, increase in sea level deviation in a storm surge, and sea level rise. It has been examined by the hydraulic model experiment that the deformation of the wave dissipating blocks covering the front face of the breakwater caisson is increased by the change of the sea conditions. In addition, the change in the hydraulic performance due to the deformation of the wave dissipating blocks is confirmed by numerical simulation. The following conclusions are obtained.

With respect to the deformation of wave dissipating blocks;

(1) The deformation of the wave dissipating blocks increases with the wave height. However, if the increase of wave height is within the stability range difference between the required mass and the applied mass, the influence of wave height increase on deformation of the wave dissipating blocks may be small.

(2) Due to the rise in sea level and the increase in sea level deviation in storm surge, if the high waves act at a higher water level than before, the deformation of the wave dissipating blocks becomes large.

(3) When the number of waves exceeding the design wave height increase, deformation of the wave dissipating blocks progress. In the range of the number of waves 3000 exceeding the design wave height, the progression of the deformation of the wave dissipating blocks become somewhat gentle as the number of waves increase.

(4) The deformation of the wave dissipating blocks under the condition that the wave is perpendicularly incident to the breakwater is larger than that under the condition that the wave is obliquely incident.

With respect to the hydraulic performance of the wave dissipating blocks;

(5) In the change of hydraulic performance due to the reduction of the crest width of the wave dissipating blocks, the change of the transmission wave height and the reflected wave height are small but the increase of the wave pressure acting on the caisson is large.

(6) The change of hydraulic performance due to the lowering of the crest of the wave dissipating blocks is greater than that due to the reduction of crest width of the wave dissipating blocks.

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