Stability evaluation on the block reinforcement for Tsunami resilient breakwater

Évaluation de stabilité sur le renforcement de bloc pour le brise-lames résistant Tsunami

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ABSTRACT: In order to improve the stability of breakwater due to overflow and seepage flow under tsunami condition, a series of hydraulic model experiment for the model of Kamaishi Harbor Mouth Breakwaters was conducted in terms of the dimension of block reinforcement such as weight, open ratio and layout pattern. As the result from this study, following conclusions were obtained. 1) This paper proposed a formula to calculate the stable weight of block reinforcement on the breakwater foundation in consideration of the overflow and seepage flow induced by tsunami based on the theoretical force balance among the frictional resistance of block reinforcement, the tractive force of the water flow over the caisson to the block reinforcement and seepage force thorough the breakwater foundation. 2) It is experimentally confirmed that seepage failure of rubble mound on the harbor-side of breakwater firstly occurred and then the damage of breakwater was acceleralated after overflow occurred. The proposed formula is effective for evaluating seepage failure and scouring of rubble mound under tsunami condition. 3) The damage of breakwater becomes smallest when the block reinforcements are disposed with the height ratio of 3/4 and the triangulate layout.

RÉSUMÉ : Pour améliorer la stabilité de brise-lames dû de déborder et l'écoulement de suintement sous la condition tsunami, une série d'expérience modèle hydraulique pour le modèle de brise-lames de baie de Kamaishi a été conduite du point de vue de la dimension de renforcement de bloc tel que le poids, le rapport ouvert et le dessin de disposition. Comme le résultat de cette étude, suite aux conclusions ont été obtenus. 1) Ce papier a proposé une formule pour calculer le poids ferme de renforcement de bloc sur la fondation de brise-lames en considération du débordement et de l'écoulement de suintement incité par tsunami basé sur la balance de force théorique parmi la résistance à friction de renforcement de bloc, la force de traction de l'écoulement d'eau sur le caisson au renforcement de bloc et au suintement force consciencieux la fondation de brise-lames. 2) Il est expérimentalement confirmé que l'échec de suintement de monticule de décombres sur le côté du port de brise-lames s'est produit premièrement et ensuite le dommage de brise-lames était acceralated après que le débordement s'est produit. La formule proposée est efficace pour évaluer l'échec de suintement et éroder du monticule de décombres sous la condition tsunami. 3) Le dommage de brise-lames devient le plus petit quand les renforts de bloc sont disposés avec le rapport de hauteur de 3/4 et de la disposition triangulaire.

KEYWORDS: breakwater, tsunami, stability, overflow, seepage, water pressure.

1 INTRODUCTION

The 2011 off the Pacific Coast of Tohoku Earthquake with the magnitude of 9.0 attacked Japan on the 11th of March, 2011. The 2011 off the Pacific Coast of Tohoku Earthquake was the heaviest earthquake in Japan ever recorded in the history. The tsunami preventing breakwaters at the mouth of Kamaishi Harbor (called Kamaishi Harbor Mouth Breakwaters herein), which are the deepest breakwaters in the world, have been experienced the catastrophic damage due to this disaster. As for the possible causes of failure of Kamaishi Harbor Mouth Breakwaters, 1) the tsunami impact force to the caisson, 2) the horizontal static force generated by the difference of water level between sea-side and harbor-side of the caisson, 3) the impact to the rubble mound due to the overflow and 4) the rapid current around the caisson are considered from the hydraulic point of view. In addition, the reduction of bearing capacity due to the seepage flow in the rubble mound is pointed out from the geotechnical point of view.

The seepage-induced instability problem has been studied extensively in the field of geo-technical engineering (Zen et al. 2013, Kasama et al. 2013, Takahashi et al. 2014). Under tsunami conditions, it is considered very significant to investigate the effect of seepage flow onto the stability of breakwaters. For a long time, Hudson's equation (Hudson, 1959) and Isbash's equation (Coastal Engineering Research Center, 1977) have been used to evaluate the stability of rubble mound for breakwater foundation against wind-induced waves. This paper presents a formula to calculate the stable weight of block reinforcement underneath breakwater foundation in consideration of the overflow and seepage flow induced by tsunami based on the theoretical force balance between frictional resistance of rubble mound, the tractive force of the water flow over the caisson to the rubble mound and seepage force thorough underneath breakwater foundation. A series of hydraulic model experiments were conducted on the scale of 1/100 for Kamaishi Harbor Mouth breakwaters as the subject in order to confirm the effectiveness of the proposed formula. Using the test results, the stability of the block reinforcement underneath breakwater foundation was evaluated from the geotechnical engineering point of view as well as hydrodynamical point of view.

2 FORMULA FOR STABLE WEIGHT OF RUBBLE-MOUND AND BLOCK REINFORCEMENT

Figure 1 shows the schematic diagram of caisson-type breakwater under tsunami condition. The height of caisson is H while the width is B. The water heights on the sea-side and harbor-side are $H+h$ and d_2 from the top of the rubble-mound respectively.

Figure 2 shows the force the balance for an individual block reinforcement on the surface of rubble-mound with the inclined angle θ among the effective weight of rubble W', the water impact force F_w from over flow, seepage force to rubble F_s, the resistance force R acting to one rubble. The critical hydraulic gradient i_c for the seepage failure of the individual rubble with the inclined angle θ is given by the following equation.

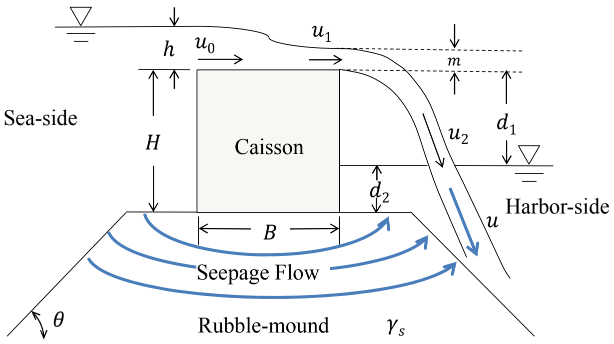


Figure 1. The overflow and the seepage flow around breakwater.

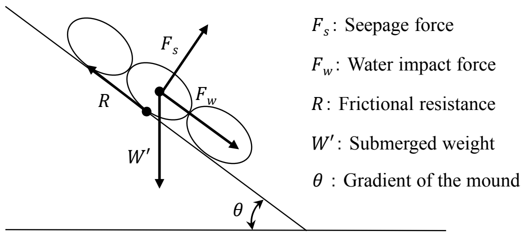


Figure 2. Schematic diagram of external forces acting on the rubble.

$$i_c = \frac{G_s - 1}{1 + e}\cos\theta \qquad (1)$$

e: void ratio, G_s: specific weight of block reinforcement.

A formula to calculate the stable weight of individual rubble mound and block reinforcement W_s underneath breakwater foundation in consideration of tsunami-induced overflow and seepage flow was proposed based on the Isbash's equation as the following form.

$$W_s = \frac{k_a^3 \gamma_s C_D u^6}{8k_v^2 g^3\left[\left\{\left(f_r\cos\theta - \frac{1+e}{G_s-1}i\right) - \sin\theta\right\}(G_s-1)\right]^3} \qquad (2)$$

C_D: resistance coefficient, *u*: the velocity of overflow [m/s], *g*: acceleration of gravity [m/s^2], γ_s: unit volume weight of the block reinforcement [kN/m^3], f_r: frictional coefficient, *i*: hydraulic gradient, k_v: volume coefficient, k_a: area coefficient.

3 HAYDRAULIC MODEL EXPERIMENT FOR KAMAISHI HARBOR MOUTH BREAKWATERS

Figure 3 shows the layout of test apparatus used in the experiment. A physical model of 1/100 in scale of Kamaishi Harbor Mouth Breakwaters was installed in a water tank. Pumps were used to reproduce the difference of water level on two sides of the model caisson. Three model caisson is used. The dimension of center caisson model is 185 mm in breadth, 195 mm in height and 190 mm in depth while the dimension of both end caissons set on the wall is 185 mm in breadth, 195 mm in height and 105 mm in depth. The weight of center caisson model is 136.4 N with the density of 2.03 g/cm^3 while the weight of both end caisson model is 75.4 N with the density of 2.03 g/cm^3. Tap water was used as a fluid in the water tank.

The hydraulic gradient *i* were represented by the pore water pressures measured in the model rubble mound using the pore pressure gauges. Figure 3 also shows the distribution of pore pressure gauges in the model rubble mound. The pore pressure gauges collected the data when the hydraulic head differences were created steady state for a given hydraulic head difference. The water height sensors on the sea-side and harbor-side and

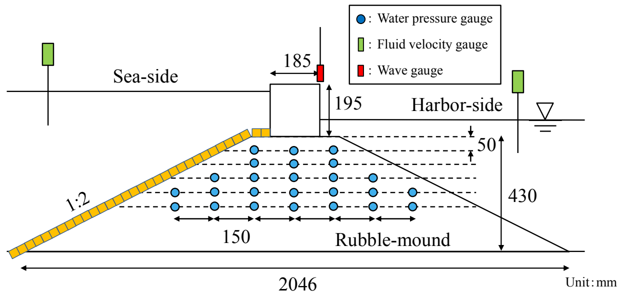
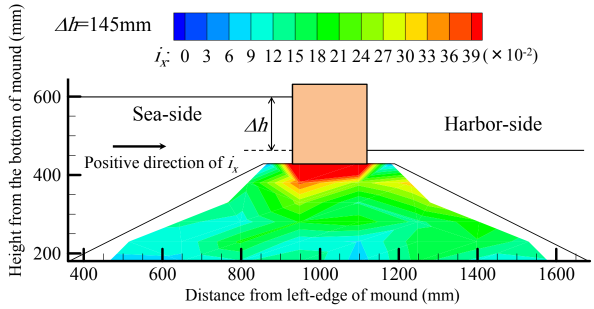


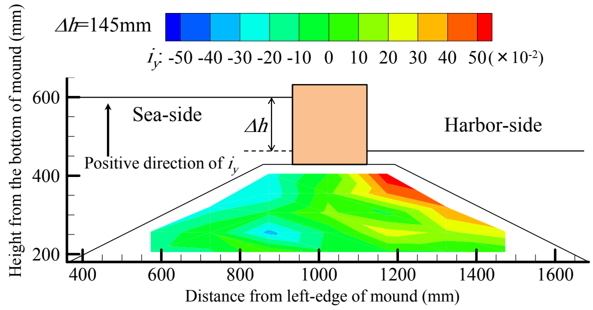
Figure 3. Schematic diagram of testing apparatus.

Table 1. test condition.

Model		Kamaishi Harbor Mouth Breakwaters (1/100)	
Caisson	Size	Height 195 mm × Breadth 185 mm × Depth 190 mm	
	density	2.03 g/cm^3	
Rubble -mound	Size	Gradient 1:2, Upper base 326 mm, Lower base 2046 mm, Height 430 mm	
	Particle size	Case 1	Case 2
		2 mm - 4.75 mm	2 mm -19 mm
	Particle weight *W*	0.002 N - 0.005 N	0.002 N - 0.027 N
	Saturated density γ_{sat}	1.86 g/cm^3	2.09 g/cm^3
	Specific gravity G_s	2.700	2.700
	Void ratio *e*	0.9763	0.5603



a) horizontal direction (the head difference of 145 mm).



b) vertical direction (the head difference of 145 mm).

Figure 4. Hydraulic gradients for Case 1.

the fluid velocity gauge above the caisson are installed to calculate the water velocity of overflow. The hydraulic head differences adopted in the tests were 0 mm, 40 mm, 80 mm 120 mm, 145 mm, 185 mm and 210 mm.

Table 1 shows the test condition of this experiment. Case 1 used gravels from 2 mm to 4.75 mm as an individual rubble while Case 2 used gravels from 2 mm to 19 mm. The saturated density was 1.86 g/cm^3 for Case 1 and 2.09 g/cm^3 for Case 2. The rubble-mound was set using rubbles in three layers. In order to adjust the density of the rubble-mound, the rubble layer for the thickness of 150 mm was piled and then compacted with the weight of hammer 70 N.

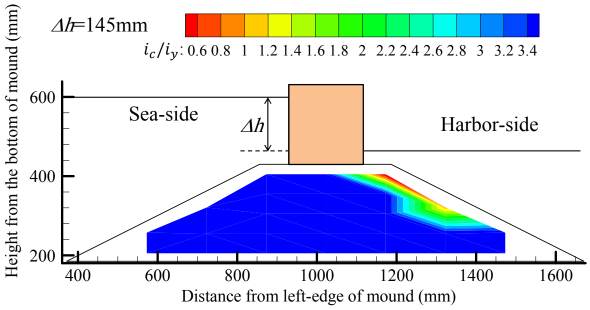
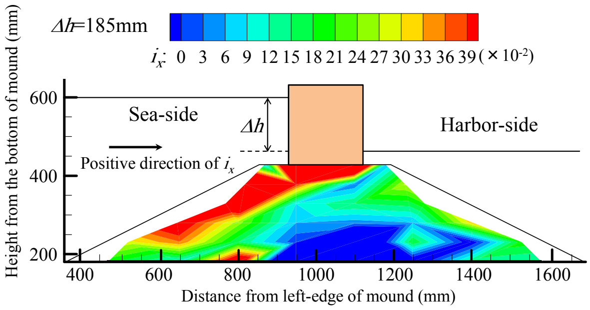
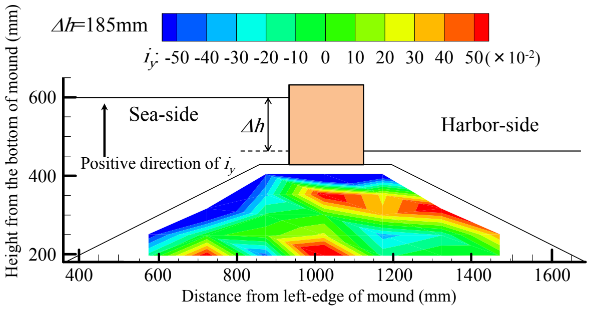


Figure 5. Instability evaluation against seepage flow for Case 1.



a) horizontal direction (the head difference of 145 mm).



b) vertical direction (the head difference of 145 mm).

Figure 6. Hydraulic gradients for Case 1.

3.1 *Instability evaluation against seepage flow.*

In order to clarify the seepage failure of the rubble-mound, Figure 4 shows horizontal and vertical hydraulic gradients for Case 1 with the head difference of 145 mm calculated from the porewater pressure measurements. It is found for Case 1 that the horizontal hydraulic gradient just beneath caisson shows largest value and the vertical hydraulic gradient on the top of rubble mound on the harbor-side of the caisson shows the largest value suggesting that vertical seepage force is remarkable.

In order to evaluate the stability of rubble-mound against seepage failure, the ratio of measured hydraulic gradient and the critical hydraulic gradient i_c calculated by Equation (1) for Case 1 is shown in Figure 5. It is noted that the critical hydraulic gradient i_c for Case 1 is 0.745 for inclined rubble of $\theta = 30$ ° and 0.861 for horizontal rubble of $\theta = 0$ ° for where $G_s = 2.7$ and $e = 0.9763$. When the head difference of 145 mm, the i_c/i drastically reduce on the top-edge and harbor-side of rubble mound, which agree with the occurrence of seepage failure of harbor-side rubble-mound observed in experiment. It is emphasized that Equation (1) can evaluate the seepage failure of rubble-mound due to tsunami-induced seepage flow.

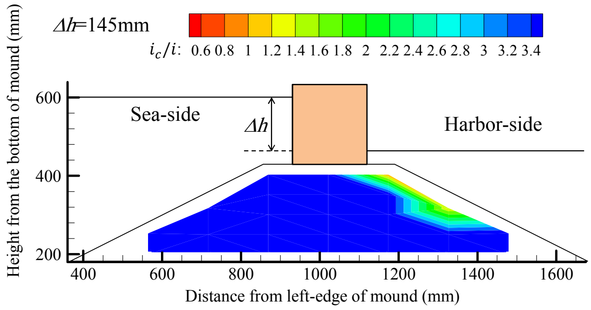


Figure 7. Instability evaluation against seepage flow for Case 2.

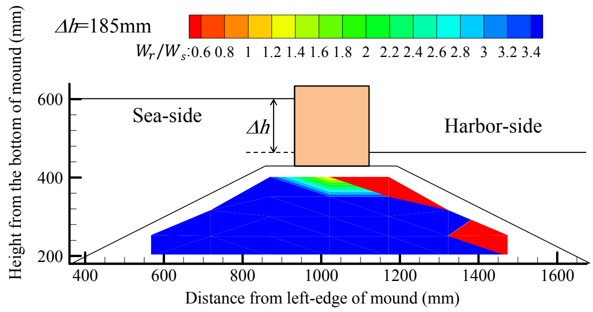


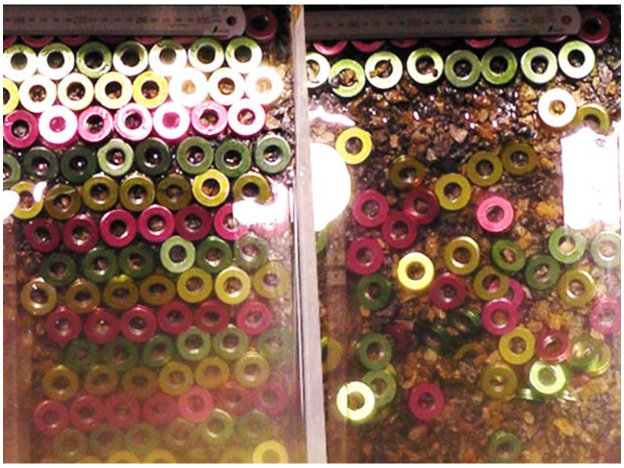
Figure 8. Instability evaluation against overflow for Case 2.

3.2 *Instability evaluation against the combination of overflow and seepage flow.*

In order to investigate the failure mechanism of the rubble-mound, Figure 6a) shows a horizontal hydraulic gradients for Case 2 calculated from the measurements. It is found for Case 2 that the horizontal hydraulic gradient just beneath caisson and sea-side of rubble mound increases with increasing water level difference. Figure 6b) shows vertical hydraulic gradients for Case 2 when the water level difference is 185 mm. It is found that the distribution of vertical hydraulic gradient is very complex due to swirl on the surface of harbor-side generated by the overflow of caisson and seepage flow through the rubble-mound simultaneously generated.

In order to evaluate the stability of rubble-mound against seepage faiure, the ratio of measured hydraulic gradient and the critical hydraulic gradient i_c calculated by Equation (1) for Case 2 with the water level difference of 145 mm is shown in Figure 7. It is noted that the critical hydraulic gradient ic for Case 2 is 0.944 where $G_s = 2.7$, $e = 0.5603$ and $\theta = 30$ °. When the head difference of 145 mm and 185 mm, the i_c/i at all areas in rubble mound is more than 1.0, which confirms that the seepage failure of rubble-mound does not occur in experiment.

In order to evaluate the stability of rubble-mound against overflow and seepage flow, the ratio of representative rubble weight W_r and the stable weight of rubble W_s calculated by Equation (2) for Case 2 with the water level difference of 185 mm is shown in Figure 8. The shape of individual rubble is model as an ellipsoid body with the ratio of short axis and long axis = 5 : 8 meaning that k_v and k_a are 0.5234 and 0.2094 respectively. It is assumed that representative rubble weigh is average rubble weigh as 0.024 [N/each], the resistance coefficient C_D is 0.1 and the frictional coefficient f_r is $\tan\phi'$ with the internal frictional angle $\phi' = 35$ °. It can be seen that he reduction of the ratio of representative rubble weight W_r and the stable weight of rubble W_s on the harbor-side of rubble-mound, particularly for top edge of rubble-mound. It is emphasized that Equation (2) can evaluate the stability of rubble-mound due to tsunami-induced overflow and seepage flow.



a) before experiment. b) after experiment.
Photo 1. Damage of block reinforcement.

4 BLOCK REINFORCEMENT

In order to improve the stability of breakwater due to overflow and seepage flow under tsunami condition, a series of hydraulic model experiment for the model of Kamaishi Harbor Mouth Breakwaters was conducted in terms of the dimension of block reinforcement such as weight, open ratio and layout pattern. The basic shape of block reinforcement was a hollow cylinder with the height ratio H/R of 1/4, 1/2 and 3/4, and the aperture ratio O of 0.3 and 0.4, which is the ratio of void area per unit area. In addition, triangulate and squire layouts were used to set block reinforcements. It is noted that H and R are the height and outer diameter of block reinforcement respectively.

Photo 1 shows the block reinforcement with the H/R of 1/2 and triangulate layout before/after overflow experiments. It can be sheen that block reinforcements move due to the impact of overflow and seepage flow downward of bobble-mound.

Figures 9 and 10 illustrate the damage ratio D of block reinforcement against water level difference between sea and harbor side. It is noted that Equation (3) was used to calculate damage ratio D when an individual block reinforcement is moved horizontally, that is judged to be damaged.

$$D = \frac{\textit{The number of damaged block reinforcements}}{\textit{The total number of block reinforcements}} \times 100[\%] \quad (3)$$

Regardless of the difference of layout, it is clear that the damage ratio D decreases with increasing the height ratio H/R. Moving block reinforcement were seen in any case before Δh is around 120 mm at which overflow occurred. This is because they were floated by seepage flow through the rubble mound. After that, each damage ratio D accelerates and the block reinforcements located at the impact point where overflow water dives were damaged from the test results, the damage of breakwater becomes smallest when the block reinforcements are disposed with the height ratio of 3/4 and the triangulate layout.

5 CONCLUSION

In order to improve the stability of breakwater due to overflow and seepage flow under tsunami condition, a series of hydraulic model experiment for the model of Kamaishi Harbor Mouth Breakwaters was conducted in terms of the dimension of block reinforcement such as weight, open ratio and layout pattern. As the result from this study, following conclusions were obtained.

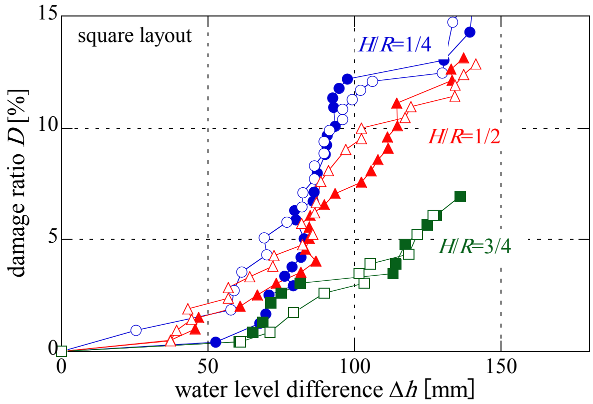


Figure 9. Damage ratio of block reinforcement with square layout.

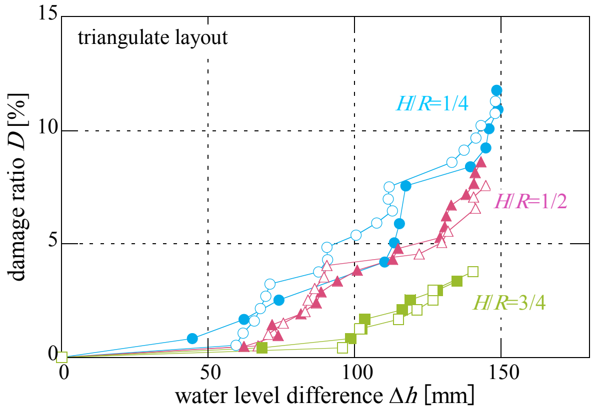


Figure 10. Damage ratio of block reinforcement with triangulate layout.

1) It is experimentally confirmed that seepage failure of rubble mound on the harbor-side of breakwater firstly occurred and then the damage of breakwater was acceralated after overflow occurred.
2) The proposed formula to calculate the stable weight of block reinforcement on the breakwater foundation in consideration of the overflow and seepage flow induced by tsunami is effective for evaluating seepage failure and scouring of rubble mound under tsunami condition.
3) The damage of breakwater becomes smallest when the block reinforcements are disposed with the height ratio of 3/4 and the triangulate layout.

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