Hydraulic Experiment on Time Varying Scour by Tsunami Overflowing

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ABSTRACT

To clarify the effect of water cushion on the scour depth caused by tsunami, a series of experiments changing the water depth behind caisson was carried out in this study. As a result, followings were clarified. Deeper the water depth behind caisson, scour depth caused by overflowing tsunami is smaller. This indicates that water behind caisson can be a water cushion for sandbed scour. Also, the scour depth is affected by not only water jet strength but also the scale of eddy depending on the interaction of water jet and rubble mound.

INTRODUCTION

In 2011, many breakwaters of Tohoku area were damaged by huge tsunami induced by the 2011 earthquake off the Pacific coast of Tohoku (Tomita et al., 2012). The north breakwater of the Hachinohe Port was also heavily damaged as shown in Fig.1. Since the length of the breakwaters was long enough (7km) compared with the length of breakwater opening (0.9km), a large tsunami overflowed the caissons, and overflowing current induced the sandbed scouring behind the caissons, resulting into the sliding of the caissons as shown in Fig. 2.

In Japan, low mound composite breakwater is widely used. To reduce scour under caisson, rubble mound is firstly installed and caisson and armor blocks are installed on the mound. After the failure of the north breakwater, a lot of research has been conducted on the stability of armor rocks (blocks) covering the rubble mound against tsunami overflowing. These phenomena are 2-D and are studied using 2-D hydraulic experiments since the length of the breakwater is long enough (mostly, 0.5 to 5km).

Scour due to tsunami overflowing has been also studied. Arikawa et al. (2014) has conducted a series of hydraulic experiments and proposed a formula to estimate the maximum scour depth. They have conducted experiments to change the height of the tsunami, especially the experiments whose water depth behind the caisson was shallow. However, the cases where the water depth behind the caisson changed were limited. The water depth behind the caisson can be shallow after the tsunami receding. On the contrary, the water depth is often deep. In such a deep situation, as shown in Fig. 3, deep water may act as a cushion, and the scouring depth may become shallow. Besides, the rubble mound may affect the scouring depth. However, they have not conducted experiments on that effect.

Therefore, in this study, a series of experiments with rubble mound was performed to change the water depth behind the caisson in order to clarify the effect of the water cushion and mound on the scouring depth.

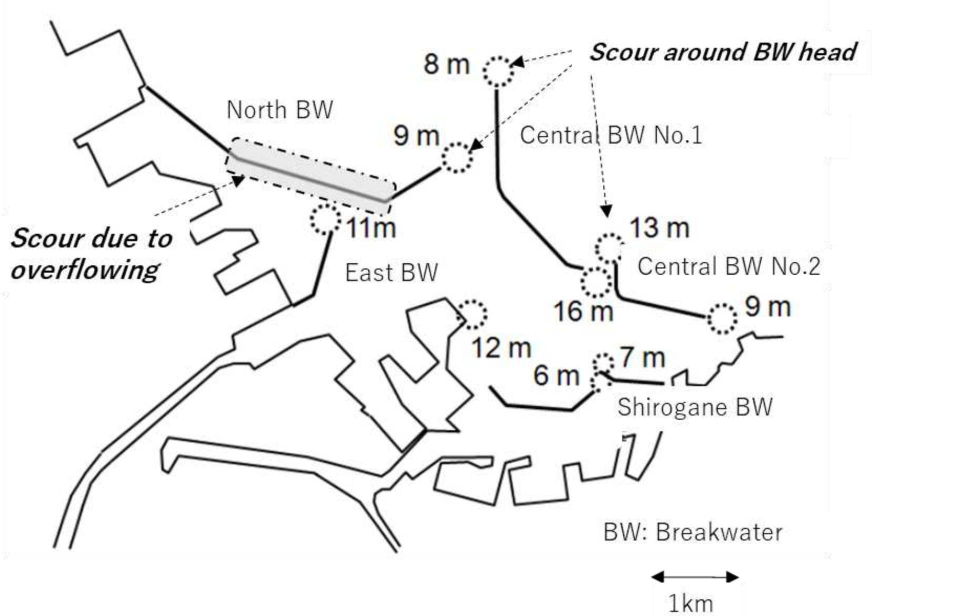

Figure 1. Scour occurred in Hachinohe Port in 2011 Tsunami.

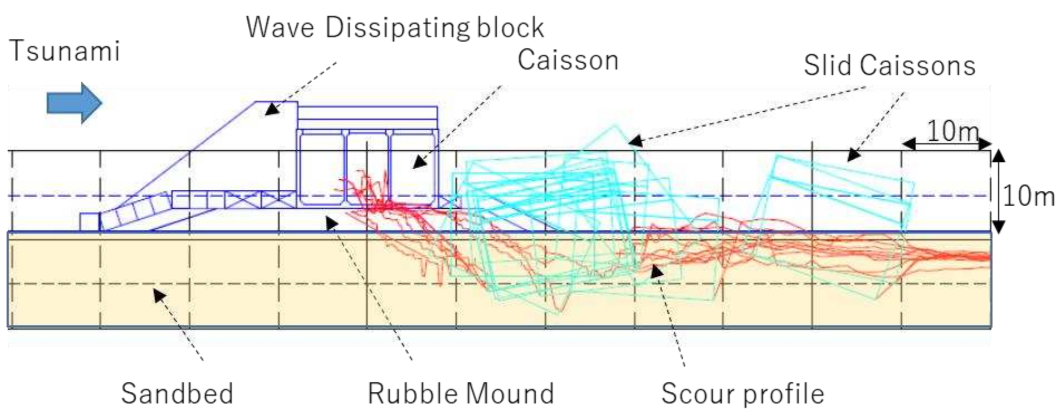

Figure 2. Failure of North Breakwater of Hachinohe Port.

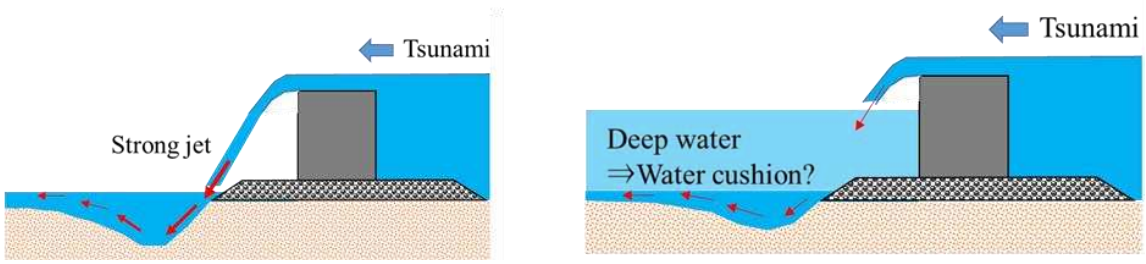

Figure 3. Schematic figure of sandbed scour due to tsunami overflowing.

EXPERIMENT

Experimental Setup. The experiment was conducted using a wave flume whose length, width is 105 m, 3m. Fig. 4 is a schematic figure of the flume. The flume is divided into the main and the secondary flume. In the main flume, 80cm deep and 300cm long sandbed were installed behind the breakwater model. The caisson model was an acrylic box whose length, height, width was 264, 320, 780mm, and was stabilized by being filled with lead. The sea floor model under the breakwater was made of concrete.

Reproduction of tsunami overflowing. Fig. 5 is a magnified view of the experimental cross section. In the field, the water level in front of the breakwater increases gradually during the tsunami approach. Overflowing starts when the water level reaches the crown height of breakwater. In this experiment, only tsunami overflowing phenomena were reproduced. Initially, water level was set higher than the caisson model. The pump behind the caisson model let down the water level and produce flow on the breakwater model, which is similar to tsunami overflowing. Pumped up water was flowed out to the secondary flume.

Sand. Fig. 6 shows the sieve curve of the sand used in the experiment. The median diameter (D_{50}) is 0.21mm. The diameter is almost as same as the field sand diameter. If we use more fine sand, wave flume becomes muddy overall and difficult to clean up. To make the experiment easy, this sand was used. To obtain more quantitative scour depth, more fine sand should be used considering the scale effect.

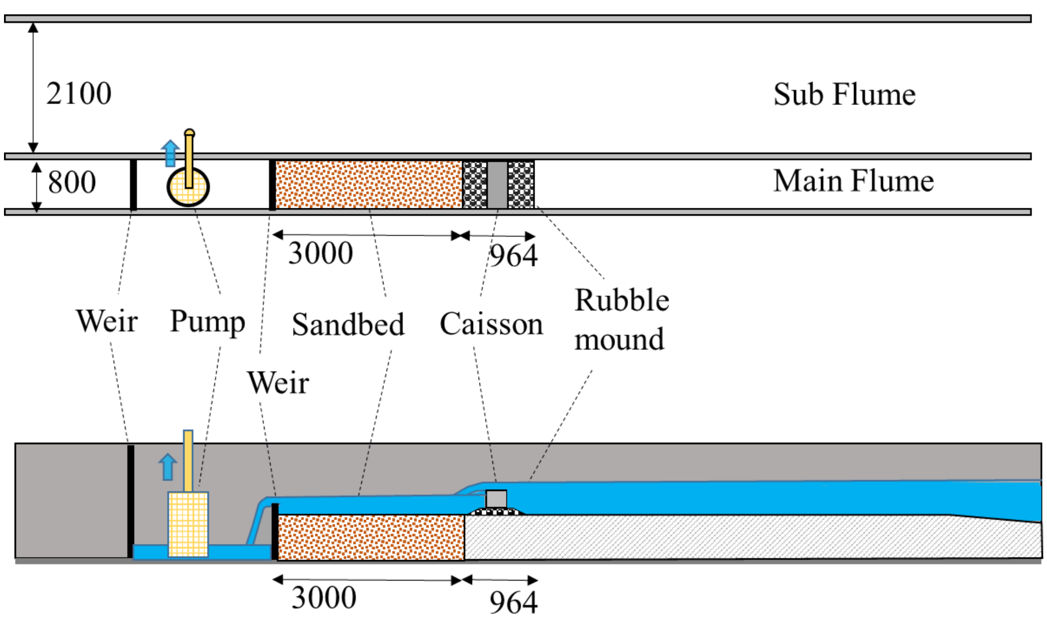

Figure 4. Schematic figure of the experimental flume.

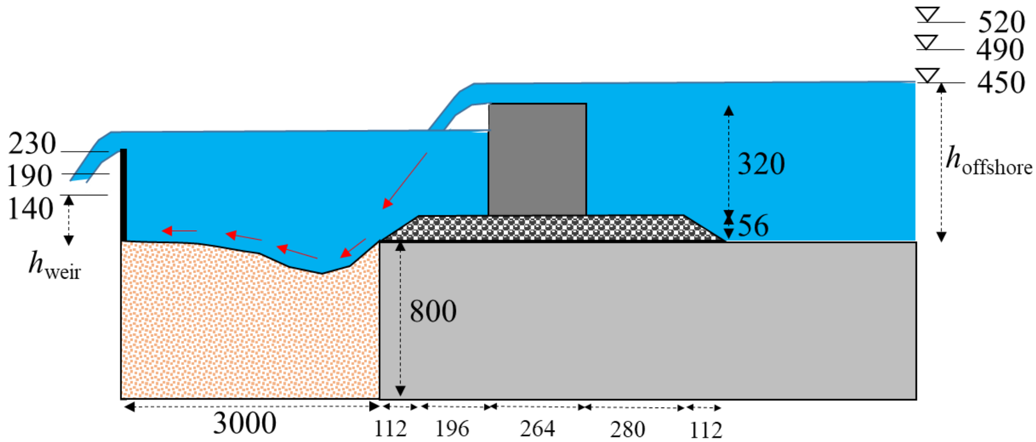

Figure 5. Magnified figure of the experimental model.

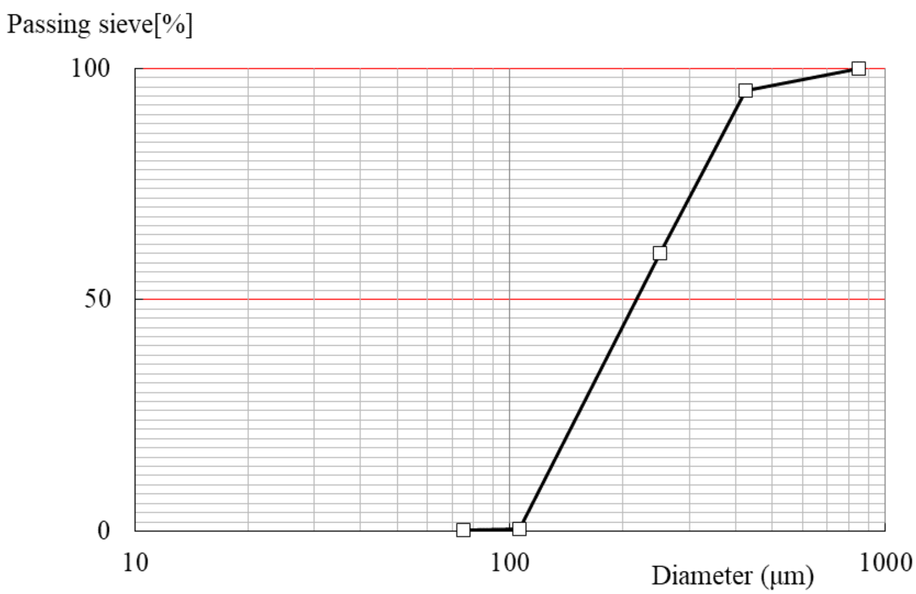

Figure 6. Sieve curve of sand.

Rubble Mound. As shown in Fig. 5, rubble mound was installed. The thickness was 56mm, and the median diameter of the rubble mound was 2.0 cm. Water flowed through rubble mound. To avoid scouring due to tsunami overflowing, rubble mound was covered by a steel net. In the field, rubble mound is covered by armor blocks.

Experimental Cases. Total 9 cases were tested varying incident tsunami height (water level in front of the caisson), water level behind the caisson and sand grain size as shown in Table 1. Initial water level was set as 450, 490 and 520cm (74, 114, 144cm) from the sea floor (the caisson). The water level behind the caisson was varied by changing the weir's height.

Table 1. Experimental cases.

case	1	2	3	4	5	6	7	8	9
$h_{offshore}$ (mm)	520	520	520	490	490	490	450	450	450
h_{weir} (mm)	230	190	140	230	190	140	230	190	140

RESULTS AND DISCUSSIONS

Figure 7 shows the time history of scour depth. The offshore water depth (initial water depth), $h_{offshore}$, is (a) 520mm, (b) 490mm and (c) 450mm, respectively. In each graph, weir height was changed from 140 to 230mm.
Here, equilibrium sour depth (S_d), overflowing depth (η_{front}), crown height of the caisson (h_{crown}), Impingement distance at surface (IP_s), Impingement distance at rubble mound (IP_{rm}) are defined as shown in Fig. 8.
Fig. 9 shows the relationship between overflowing depth (η_{front}) and equilibrium scour depth (S_d). They are nondimensionalized by crown height of the caisson (h_{crown}). Fig. 10 also shows the relationship between overflowing depth (η_{front}) and equilibrium scour depth (S_d). Here, equilibrium scour depth is nondimensionalized by overflowing depth.
From these figures, equilibrium scour depth (S_d) is almost proportional to overflowing depth (η_{front}). The maximum scour-overflowing depth ratio (S_d/η_{front}) is 4.2 to 5.5 in case 1 to 3. This ratio is almost the same as the results of Arikawa et al. (2014). However, the ratio in case 4 to 9 is much smaller than their results.
Fig. 11 shows the impingement distance at rubble mound (IP_{RM}) divided by the length of the top of rubble mound (196mm). The impingement point is away from the rubble mound in Cases 1-3, but it is inside the rubble mound in Cases 4-9. It is probable that the flow direction changed as the flow collided with the rubble mound, and the scour depth decreased in Cases 4-9.

As shown in Fig.9 and Fig.10, the equilibrium scour depth scatters even in the cases whose overflowing depth is the same. The maximum deviations (ΔSd/mean(Sd)) are 0.26, 0.25 and 0.6 in Cases 1-3, Cases 4-6 and Cases 7-9.
Fig 12 shows the relationship between scour depth (S_d/h_{crown}) and drop height of overflowing water (h_{drop}/h_{crown}). In Cases 1-3, higher the drop height, the scour depth is larger. This indicates that deep water can be a water cushion for sandbed scour.

On the contrary, in Cases 4-6 and Cases 7-9 show the opposite characteristics.
Figure 13 shows the photo of case 3. Overflowing water generated strong jet, resulting in large eddy. The scour hole occurred along this eddy.

Figure 14 and 15 show the photos of case 7 and case 9, respectively. In case 7, water jet generated an eddy, and scour occurred along this eddy. In contrast, the water jet of case 9 hit the rubble mound much harder than case 7, then the flow bounded back from the rubble mound, resulting in the directional change of the flow, and the flow moved horizontally. Because of this flow directional change, the eddy and the scour depth of case 9 were smaller than that of case 7. These results indicate that the scour depth is affected by not only water jet strength but also the scale of eddy depending on the interaction of water jet and rubble mound. Here, the water jet strength depends on the tsunami height and the water depth behind the caisson.

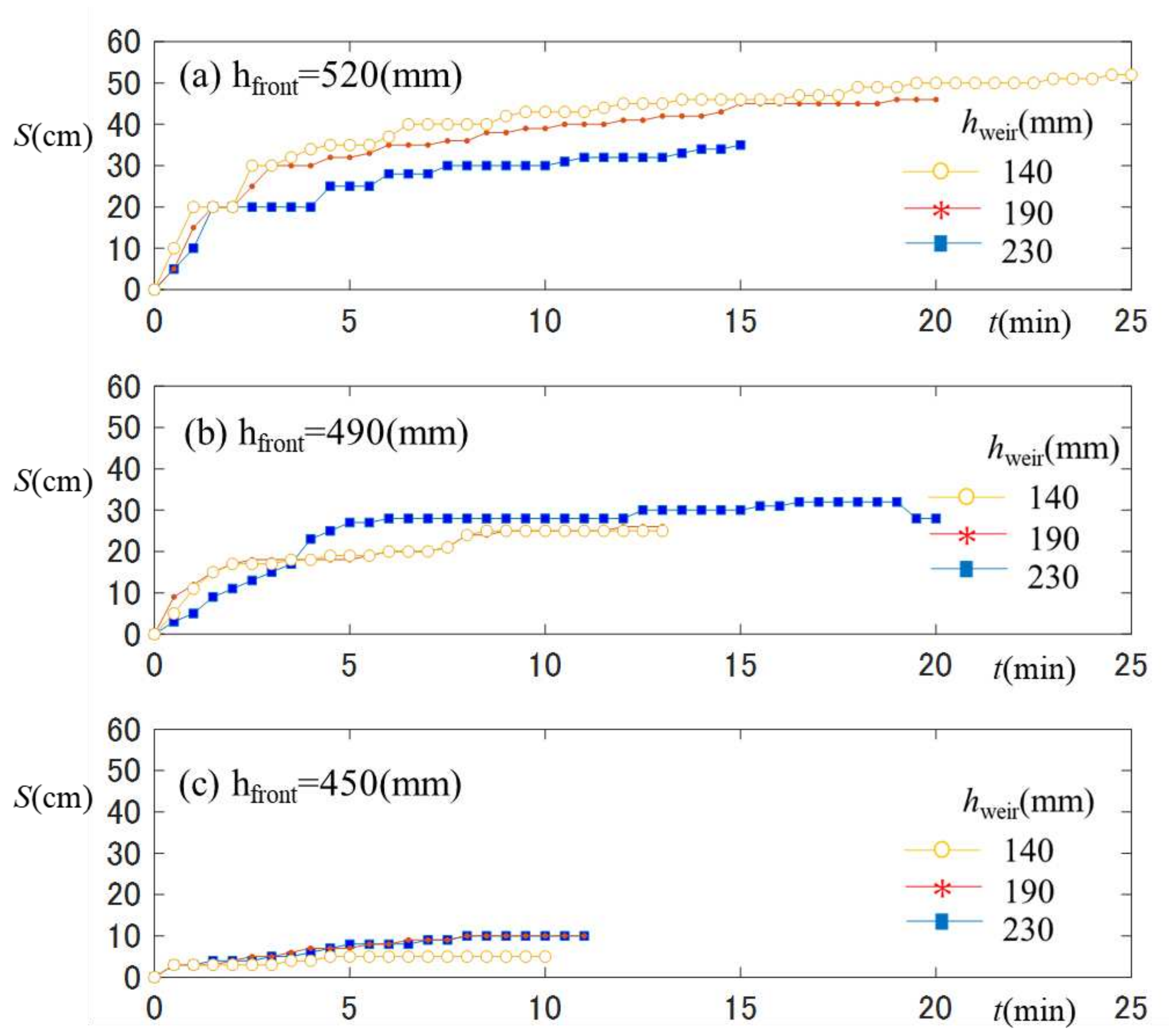

Figure 7. Time history of scour depth.

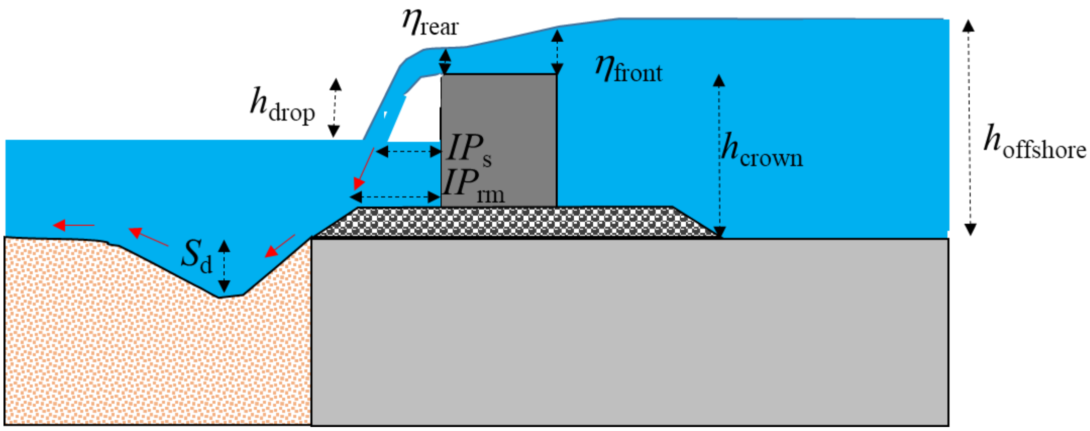

Figure 8. Definition of equilibrium sour depth (S_d), overflowing depth (η_{front}), crown height of the caisson (h_{crown}), Impingement point at surface (IP_s), Impingement point at rubble mound (IP_{rm})

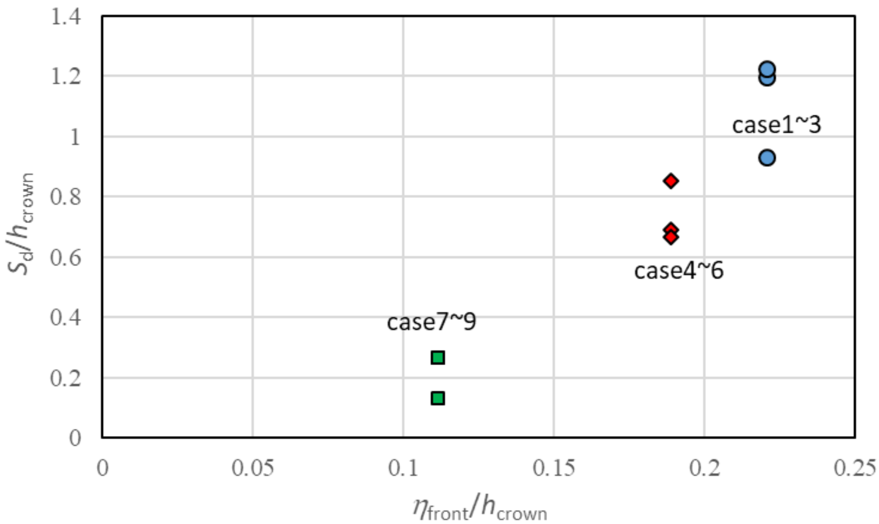

Figure 9. Relationship between overflowing depth and equilibrium scour depth.

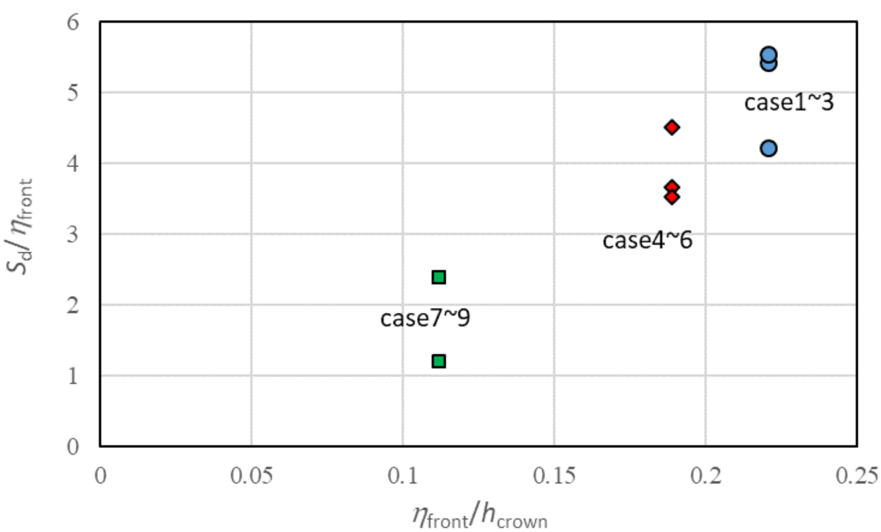

Figure 10. Equilibrium scour depth nondimensionalized by overflowing depth.

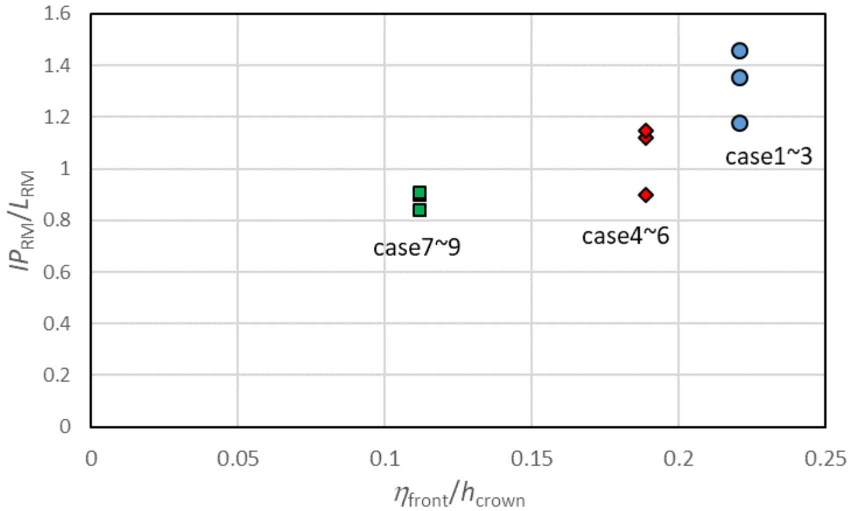

Figure 11. Impingement pint and overflowing depth

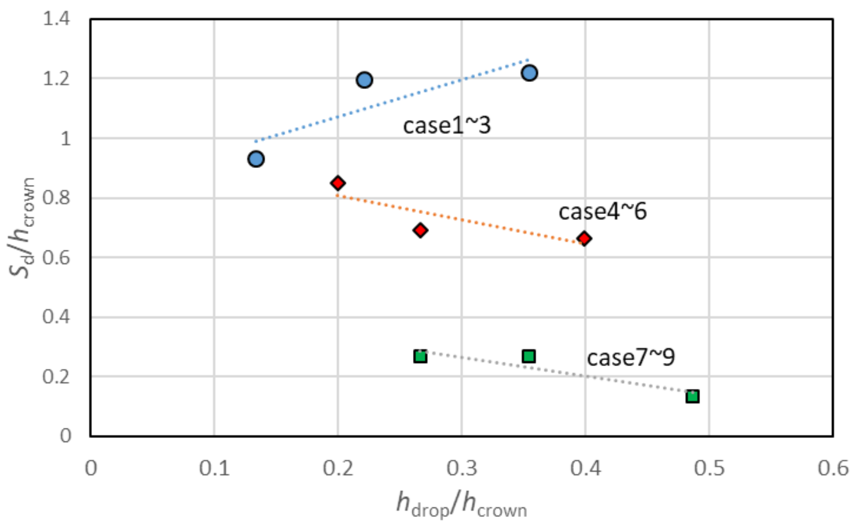

Figure 12. Relationship between scour depth and drop height of overflowing water

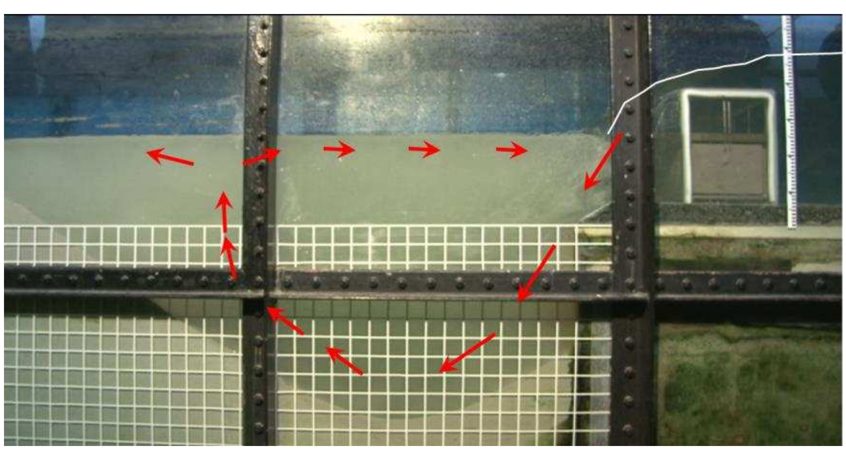

Figure 13. Eddy and scour hole generated in case 3.

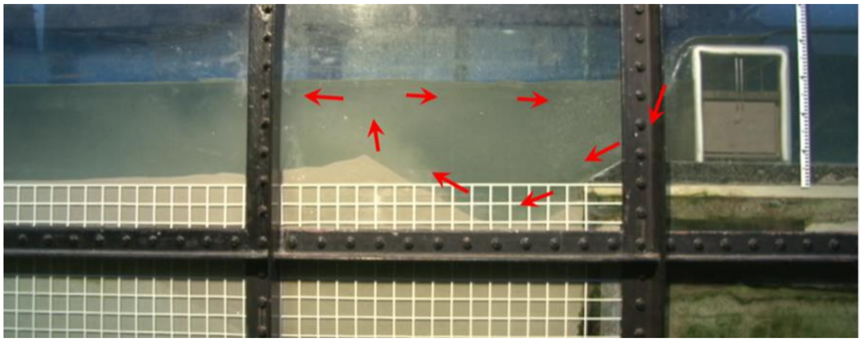

Figure 14. Eddy and scour hole generated in case 7.

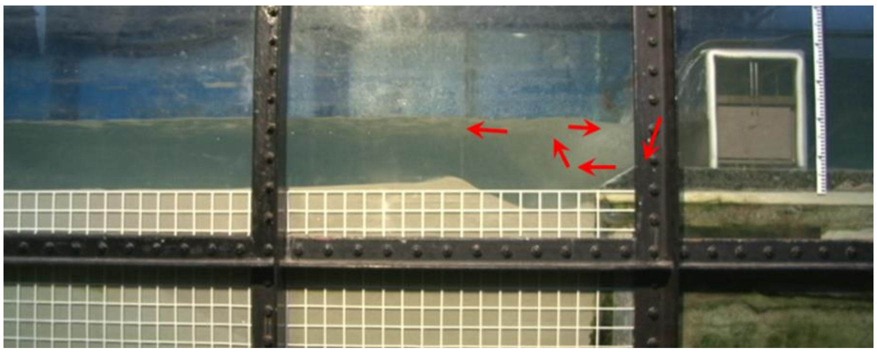

Figure 15. Eddy and scour hole generated in case 9.

CONCLUSION

To clarify the effect of water cushion on the scour depth caused by tsunami, a series of experiments changing the water depth behind caisson was carried out in this study. Total 9 cases were tested varying incident tsunami height (water level in front of the caisson), water level behind the caisson.

As a result, followings were clarified.

1) The maximum scour-overflowing depth ratio (Sd/ηfront) is 4.2 to 5.5 when the impingement point at rubble mound is away from the rubble mound. On the contrary, the ratio is much smaller when the impingement point is inside the rubble mound. It is probable that the flow direction changed as the flow collides with the rubble mound resulting in the decrease of the scour depth.

2) The equilibrium scour depth scatters even in the cases whose overflowing depth is the same. The maximum deviations (ΔSd/mean(Sd)) are 0.25 to 0.6. When the impingement point at the rubble mound is away from the rubble mound, the higher the drop height, the scour depth is larger. This indicates that deep water can be a water cushion for sandbed scour.

3) On the contrary, when the impingement point at the rubble mound is inside the rubble mound, the higher the drop height, the scour depth is smaller. This is due to the directional change of water jet due to the collision of rubble mound.

In this experiment, almost the same size of sand as in the field was used, and the problem of the law of similitude remains as a future study.

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