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Experimental Study on Backwash of Tsunami Acting on Caisson-Type Quay Wall

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Abstract: This paper examines forces of the backwash of overflowing tsunamis acting on a caisson-type quay wall through hydraulic experiments. The overflowing tsunami forces are generally estimated by a simple model based on the static pressure with compensating parameters α_f and α_r for the front and rear sides of the target caisson, respectively. The compensating parameters are known as a key factor to decide the accuracy of the estimation. However, they sometimes get too irregular values to be predicted precisely. In addition, there are still few examinations about the tsunami force acting on the quay wall. In our experiments, the tsunami forces acting on the backside and the foreside of a caisson-type quay wall are measured. In the experiment, 4 types of the caisson-type structures are applied and the fluctuation of the tsunami forces is examined. From the results, the influence of the permeability on the tsunami forces around the caisson is discussed. Moreover, the solidified rubble backfill is applied as an improvement, and its enhancement of the durability against the tsunamis is shown.

Keywords: quay wall, tsunami, backwash, overflow, wave force, solidifier, backfill, mound

1 Introduction

After the 2011 off the Pacific coast of Tohoku earthquake with the huge tsunami, researchers and engineers in the Japanese coastal engineering field are increasingly concerned about the huge earthquakes, such as the Nankai or Tonankai earthquakes and their subsequent tsunamis. In the coastal engineering field, many quays, seawalls and breakwaters have been repaired after the huge tsunami in 2011, and most of them have been improved for enhancement of the durability against tsunamis. However, the damage processes of the structures by tsunamis have not been comprehended sufficiently. A quay wall under tsunamis is one of the structures which are not sufficiently studied. In fact, thanks to support by the sand backfill, the quay walls can keep the relatively good durability against surging tsunamis. On the other hand, such a supporting force does not work under the backwash of the tsunamis, and the quay walls will get an unstable state. As an urgent subject, quay walls should be improved for protection from the backwash of tsunamis. In addition to it, they are required to be in service, in many cases, even under construction for improvements, due to the economic circumstances. Therefore, some effective and economic approach is required to achieve improvements.

As for existing studies related to the tsunami force acting on the coastal structures, some estimation methods have been proposed. However, the tsunami forces are usually accompanied by complicated fluctuations, and thus, applications of the proposed methods are limited depending on the target structures and hydraulic conditions. Arikawa et al. (2013) and Miyata et al. (2014), from the experiments targeting breakwaters with incoming and overflowing tsunamis, found that the tsunami forces get unexpected and irregular values at the back side of the structures. Tsuruta et al. (2017) proposed a new method for accurate estimation of the backside forces of overflowing tsunamis. These studies targeted breakwaters. Quay walls comprise more complicated structures, which should consider the earth pressure, the permeability of the sand backfill and the rubble mound, conditions of the pavements, and etc. Mizutani et al. (2010) examined the motions of a drifted vessel around a quay wall by a tsunami. They focused on the motions of the drifted vessel and the velocity field around the quay wall, not force acting on the quay wall. Kwang-Ho et al. (2015) showed unstable states of a quay wall, which is caused by a tsunami and an earthquake. This study applied a non-overflowing tsunami. Gi-Chun et al. (2014) showed the influence of an earthquake and an overtopping tsunami. This study treated the tip of the tsunami. As a rare study, Arikawa et al. (2013) examined the forces of backwash of tsunamis. In their experiment, it was found that the acting force disperses irregularly. There are not sufficient studies of the estimation of the overflowing tsunami forces acting on quay walls.

This study performs hydraulic experiments with targeting a caisson-type quay wall under backwashes of tsunamis. In the experiments, the forward and backward wave forces acting on the quay wall are measured. Here, 4 types of surroundings are applied to the experiments. And the permeability of the rubble/sand backfills and the rubble mound are focused on to examine their influence on the wave forces. Moreover, an effective and simple improvement approach, namely the solidification of the rubble backfill behind the caisson is proposed to enhance the durability of the quay wall against the tsunamis as one of the models.

2 Hydraulic experiment

2.1 Experimental condition

In the experiments, a 105m long flume is used. The flume is separated in the middle with 42m distance from the edge by the main and sub flumes. The main flume has a 0.8m width. The quay wall is To reproduce the backwashes of the tsunamis, a pump is set behind the quay wall model to circulate the uniform flow through the main flume and sub flume. In order to keep the water level difference between the front and back of the quay model, a movable weir is set behind the caisson as shown in Fig 1. The target water level is reproduced by adjusting the initial water level and the height of the movable weir before starting the pump.

Regarding the types of models, Type A includes a geotextile and covering sands on the rubble backfill just vicinity of the caisson, which is expected as the most impermeable type (Fig. 2). Type B includes the geotextile and covering rubbles. Type C is set without the geotextile and covering materials as the highest permeable type. This condition assumes a serious situation where the covering materials are washed away by the first attack of the target tsunami wave. Type D is set in similar to Type C, but a part of the rubble backfill is solidified to improve the impermeability. The setups of the types are shown in Tab. 1.

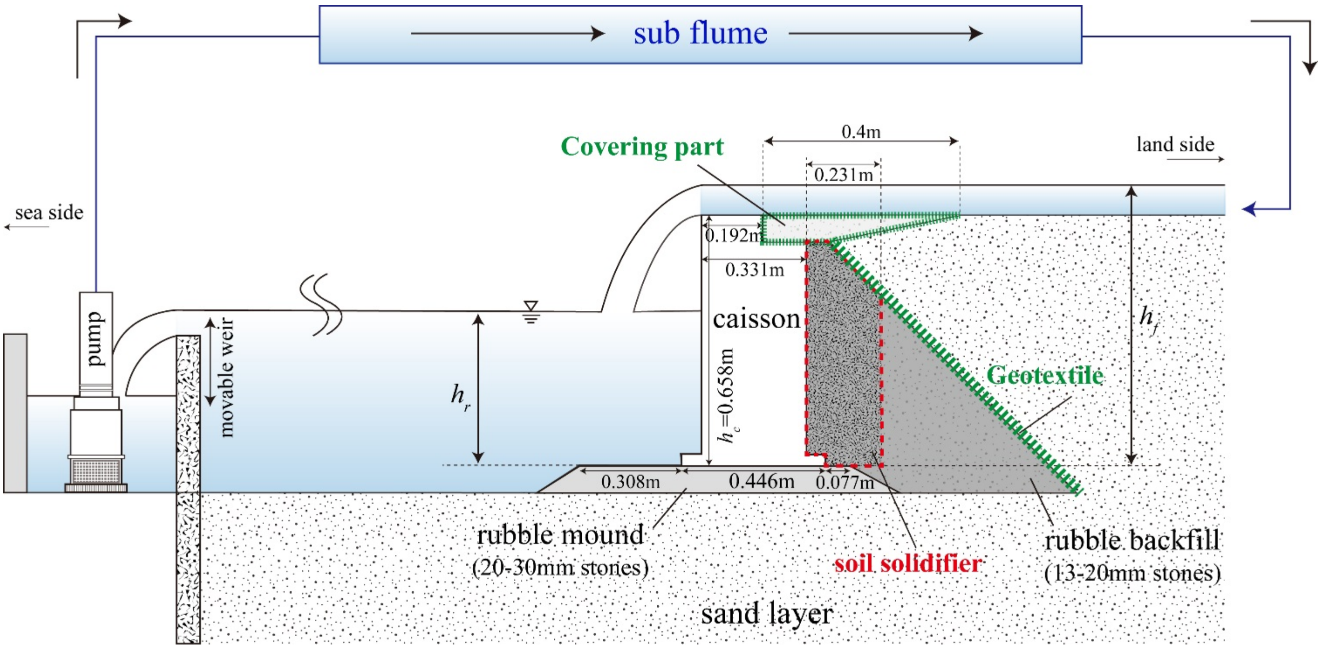


Fig. 1. Graphical presentation of the experimental condition

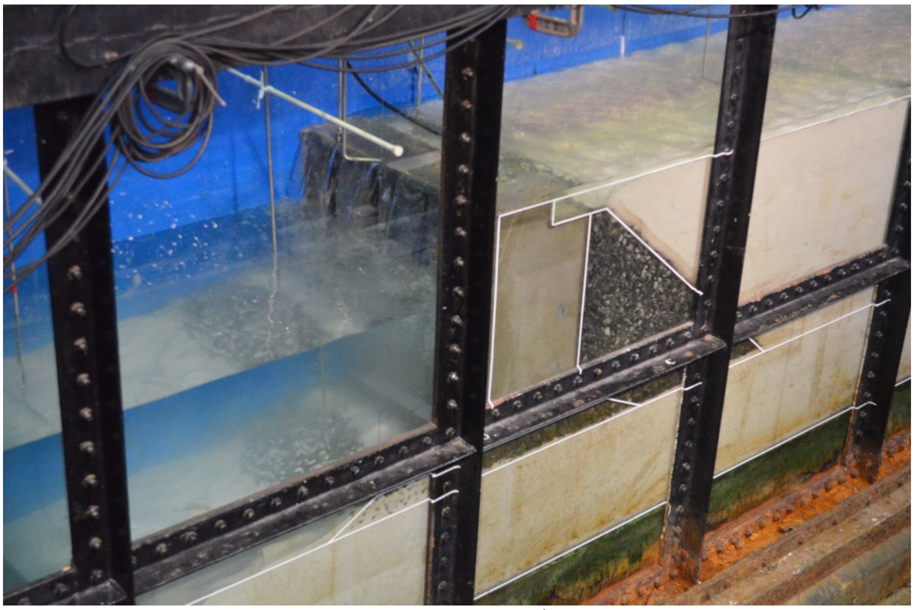


Fig. 2. Snapshot of the experiment (Type A, h_r^*=0.62)

Tab. 1. Model types and their conditions

	rubble backfill	cover	geotextile
Type A	normal	sands	✓
Type B	normal	rubbles	✓
Type C	normal	-	-
Type D	solidified	-	-

Regarding the water levels, Fig. 3 shows the relation of the water levels between rear and frond side of the caisson corresponding to h_r^* (sea side) and h_f^* (land side), respectively. The water levels are measured by the wave gauges at the 1.0m ahead and behind of the caisson. They are normalized by the height of the caisson in Fig. 3. The initial water level is set as h^*=1.05 or 1.10. The gate is adjusted to keep the side water level of the rear side with the range as $0.2h_c$ – $1.0h_c$.

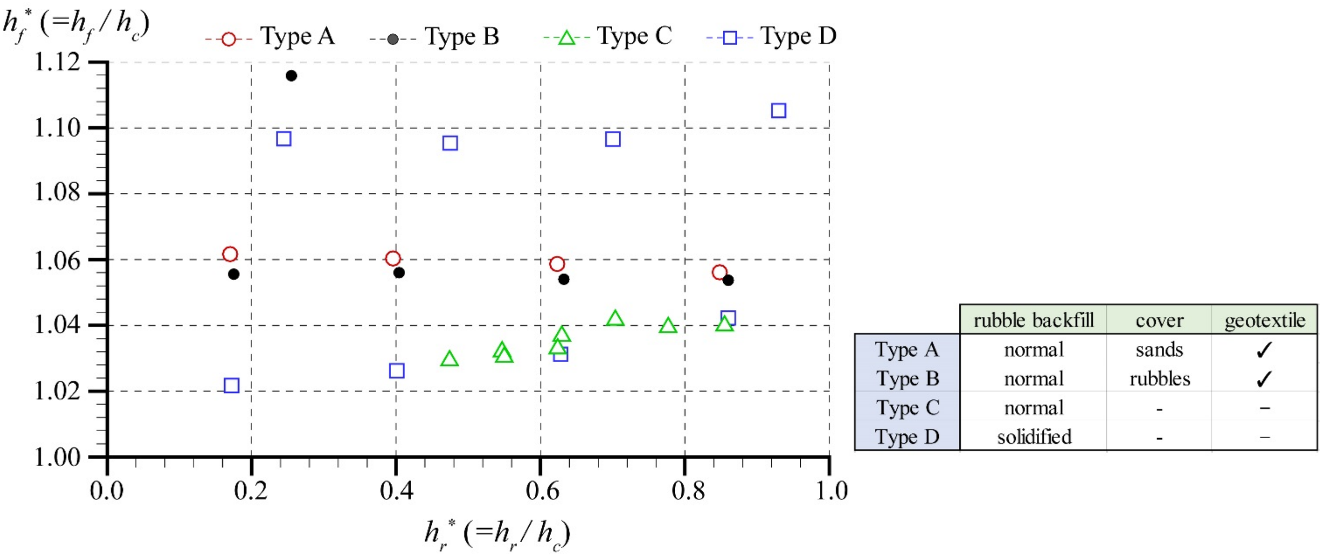


Fig. 3. Settings of the water level (h_r^* vs. h_f^*)

The water levels are defined by an averaging procedure in t=200–400s corresponding to when the overflow keeps a steady state after starting the pump as shown in Fig. 4.

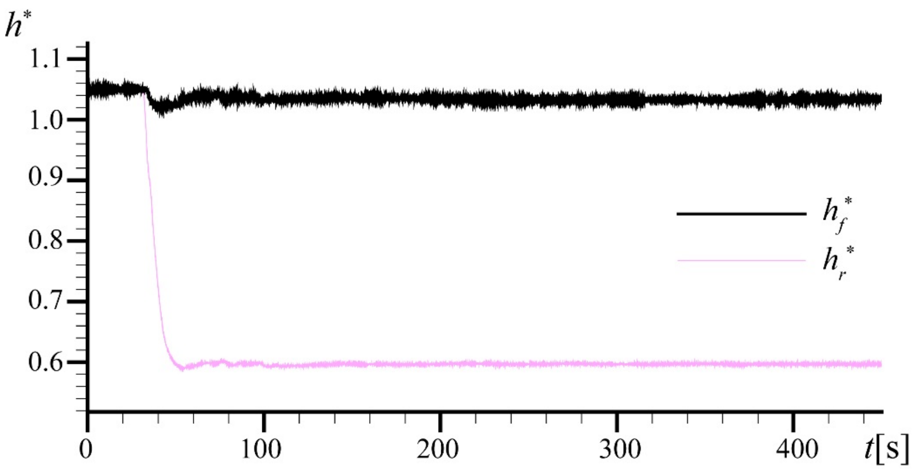


Fig. 4. Time series of the water level h_f^* and h_r^* (Type A, h_r^*=0.62)

2.2 Wave forces in the experimental results

In the Japan design guideline of breakwater against tsunami (2013), wave forces by overflowing tsunamis are estimated through the static pressure as:

$$p_1 = \alpha_f \rho_0 g h_f \tag{1}$$

$$p_2 = (h_f - h_c) p_1 / h_f \tag{2}$$

$$p_3 = \alpha_r \rho_0 g h_r \tag{3}$$

where p_1 = the wave pressure acting on the front surface at the bottom of the target caisson, p_2 = the wave pressure at the bottom of the rear surface of the caisson, p_3 = the front-side wave pressure acting on the top of the caisson, h_f = front-side water level, h_r = rear-side water level, h_c = the height of the caisson and α_r and α_f = semi-empirical parameters to compensate the static pressure at the rear and fore sides of the target caisson, respectively. These equations assume that the tsunami pressure linearly increases with the water depth as shown in Fig. 5. The estimated wave pressure would be linearly increased as the water level increases if the compensating parameters are constants. However, as mentioned by existing studies, the overflowing tsunamis deform violently the free surface at the vicinity of the back of the caisson. And as a result, the wave pressure acting on the back of the caisson irregularly changes as the water level difference increases between the backside and the foreside of the caisson. For this problem, Tsuruta et al. (2017) proposed an estimation method to define the compensating parameters and α_r accurately by using its relation to the normalized water level as:

$$h = h_f / h_r \tag{4}$$

In this study, Eq. (4) is applied to our experimental results for examination of the fluctuation of the wave force.

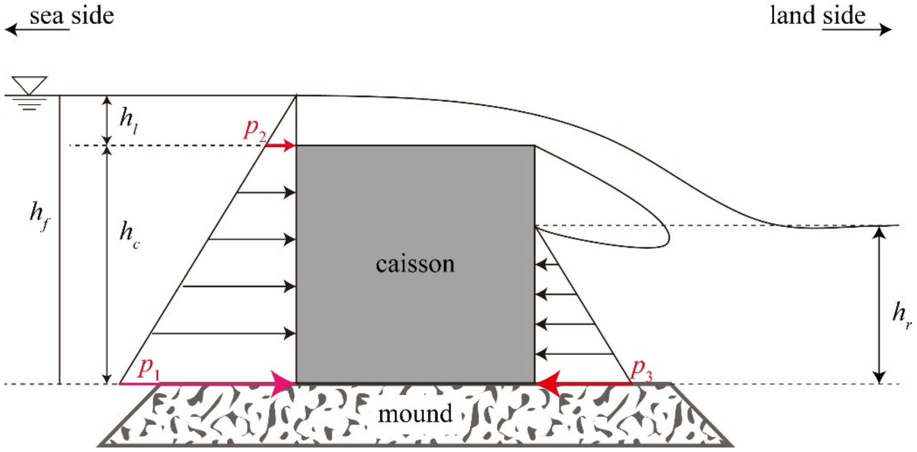


Fig. 5. Graphical presentation of estimation of overflowing tsunami force acting on a breakwater

Fig. 6 shows a snapshot with the vertical distribution of pressure on the surface of the caisson in a typical case of the present experiments, which corresponds to Type A with h_r^*=0.62. In similar to the water levels, the measured pressures are averaged in t=200–400s, when they are sufficiently stable at a developed stage as shown in Fig. 7, to define the compensating parameters α_r and α_f. In Fig. 6, red circle is the measured local pressure, the red line denotes the approximate line of measurements and the blue dash line denotes the expected vertical distribution of the static pressure estimated from the water level. By comparing the red line with the blue dash line, the compensating parameters α_f and α_r are defined.

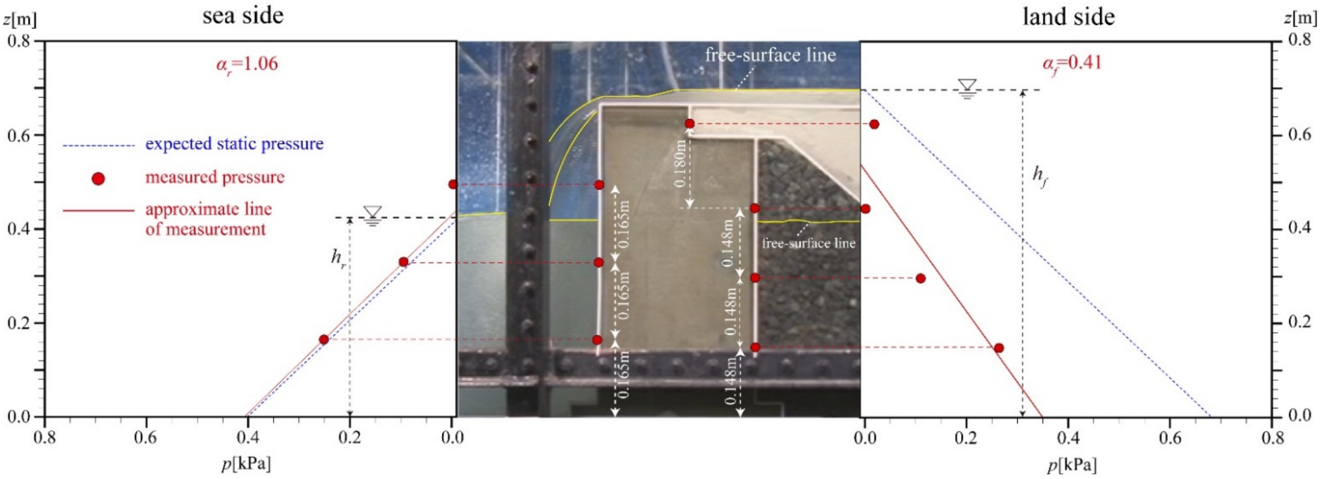


Fig. 6. Snapshot of the experiment with its vertical distribution of tsunami pressure (Type A, h_r^*=0.62)

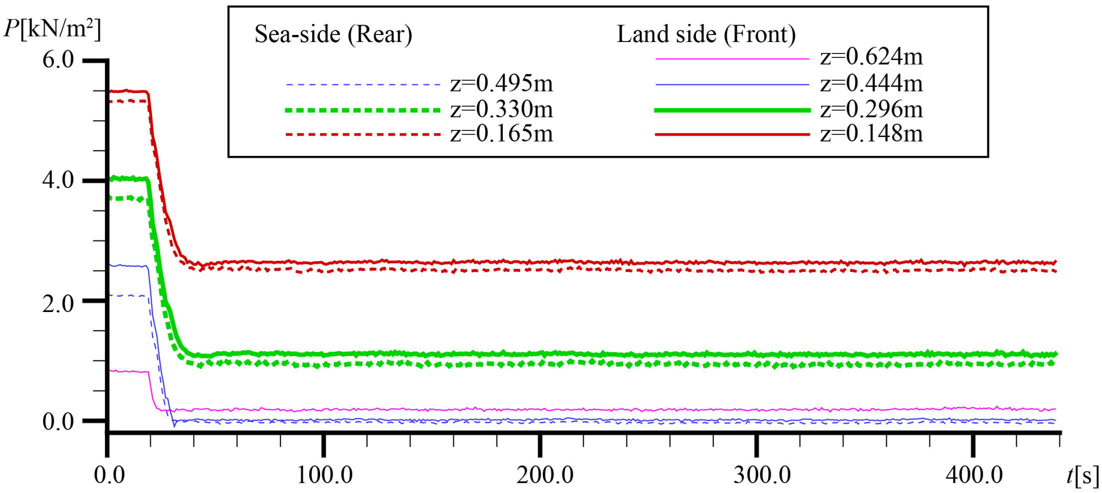


Fig. 7. Time series of the measured pressure (Type A, h_r^*=0.62)

Fig. 8 shows the obtained compensating parameters αf and αr in our experimental results. According to the existing manner, they are arranged with the normalized water level h* (= hr/hf). It is found that the rear-side (seaside) parameters αr keep stable values between 1.0 and 1.1. While, the front-side (landside) parameters αf scatter significantly. Type A corresponding to the least permeable structure decreases the front-side tsunami force relatively. Type B, which includes the rubble cover instead of the sand cover, shows bit higher forces. Type C, the most permeable structure, shows the highest front-side tsunami forces in our experiments. Type D, which solidifies the backfill rubbles, improves the situation. In the range of our experiments, permeability around the caisson effectively suppresses the front-side tsunami force.

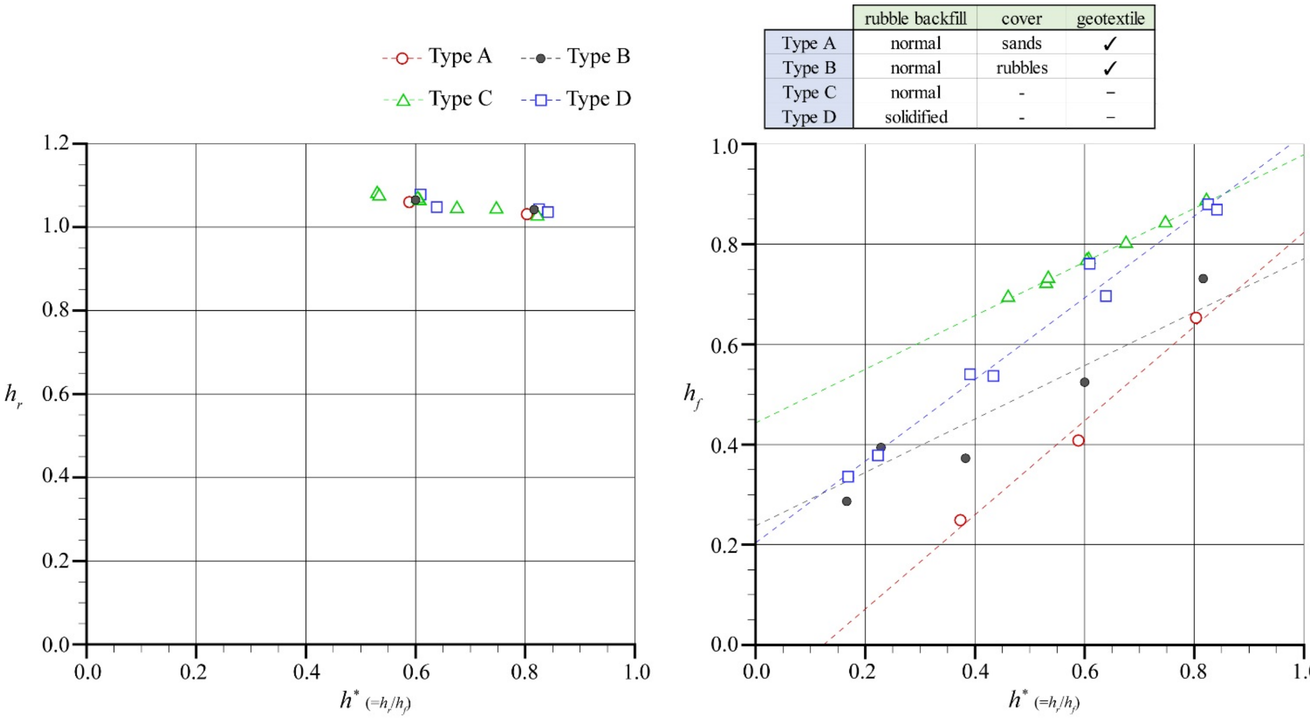


Fig. 8. The compensating parameters α in the present experiments (left: rear side (sea side), right: front side (land side))

Fig. 9 shows the total tsunami force of acting on the caisson. Type A almost cancels out the tsunami forces. Type B also relatively decreases the total tsunami forces. Type C and Type D show much higher forces. In the results of Type C and Type D, the total tsunami force apparently increases as the normalized water level decreases till the peak around h^*=0.5. However, Type D including the solidified rubble backfill decreases the total tsunami force as the normalized water level h^* decreases further from the above-mentioned peak. This implies that the caisson-type quay wall comprises the resilience in the seriously severe condition caused by the backwash of the overflowing tsunamis. This trend is shown in Type A and Type B also. The hydraulic conditions in our experiments do not cover the range over the peak in Type C, thus, such a trend has not appeared yet in Type C.

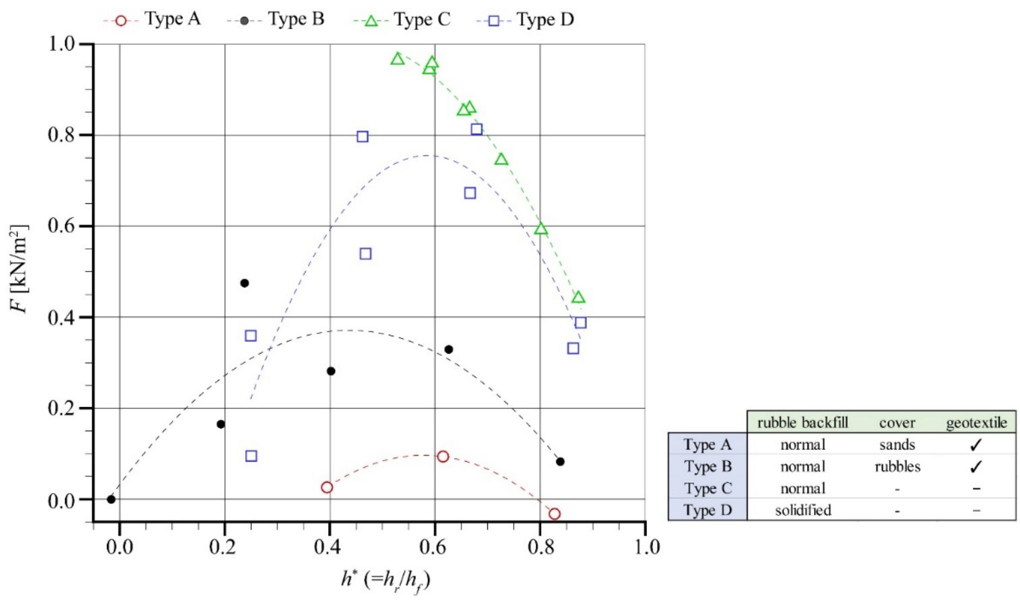
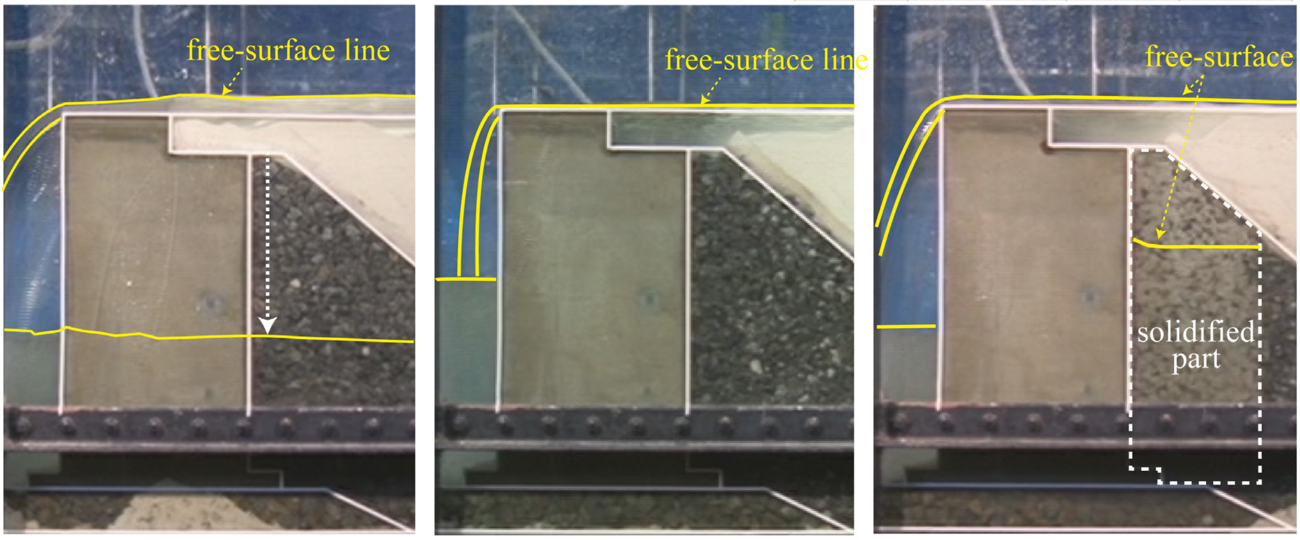


Fig. 9. Total wave force per unit width acting on the caisson

In order to clarify the effect of the permeability around the caisson, the free-surface lines in the typical cases in our experiments are shown in Fig. 10. The free-surface line is tracked by the yellow line in the figure. Type A generates an ample amount of the draining water through seepage flows compared with the supply of the water from the top. For the reason, as shown in the figure, the water level in the rubble backfill decreases and corresponds to that of the rear side (sea side) of the caisson. As a result, the total wave forces are canceled out between the rear side and front side of the caisson. Considering the damage from the large tsunami, the pavement of the quay wall can be easily broken before the following tsunamis reach or possibly the backwash of the first tsunami occurs. It will bring about undesirable permeability. Type C and D correspond to such a severe situation, which does not comprise the cover sands or the geotextile around the caisson and result in enhancement of the permeability. In the snapshot of Type C (h_r*=0.47), the free-surface line does not appear in the rubble backfill. In type C, the rubble backfill is filled with the water, and thus, the water level difference is not suppressed as in Type A. This condition supplies more water from the top of the quay wall than the amount of the draining water by the seepage flow. On the other hand, Type D improves the situation, and the free-surface line is shown in the rubble mound. The solidified part gains the impermeability and prevents the water from flowing to some extent. It achieves enhancement of the stability against the tsunami.

	rubble backfill	cover	geotextile
Type A	normal	sands	✓
Type B	normal	rubbles	✓
Type C	normal	-	–
Type D	solidified	-	–



Type A (h_r^*= 0.40)   Type C (h_r^*= 0.47)   Type D (h_r^*= 0.40)

Fig. 10. Snapshots of the typical cases in the experiments accompanied by the free-surface lines

3 Concluding remarks

This paper examined the wave forces of the backwash of the overflowing tsunamis acting on caisson-type quay walls through hydraulic experiments. In the experiments, the permeability around the caisson was focused on, that is, the influence of sand/rubble covers on the surface of the ground behind the caisson, the rubble/sand backfill, and the geotextile behind rubble backfill. Further, a part of the rubble backfill was solidified as an improved method so as to gain the stability of the quay wall against the large tsunamis.

From the experimental results, it was found that the sand cover and the geotextile are most effective to suppress the wave force acting on the caisson in our experimental conditions. They prevent the water from intrusion into the rubble backfill behind the caisson from the top of it, and result in reducing the amount of the water supply. In the condition, the amount of the draining water, which is cased by the seepage flow through the rubble mound, gets larger than that of the supply. From the experimental results, it was found that the sand cover and the geotextile are most effective to suppress the wave force acting on the caisson in our experimental conditions. They prevent the water from intrusion into the rubble backfill behind the caisson from the top of it, and result in reducing the amount of the water supply. In the condition, the amount of the draining water, which is caused by the seepage flow through the rubble mound, gets larger than that of the supply. Then, the water level decreases behind the caisson, and gets equal to the opposite-side water level. Consequently, the tsunami forces are canceled out between the rear side and front side of the caisson. If the permeability around the caisson increases due to loss of the optional structures such as the damage of the pavement on the surface of the ground, the supply of the water into the rubble backfill increases. Our experiments showed that such a situation increases the tsunami forces due to the keep of the water level difference between the rear and front sides of the caisson. However, the tsunami force can be reduced by solidifying the rubble mound, which suppresses the seepage flow. The solidification method can be expected to reduce not only the earth pressure, but also the tsunami forces.

For future works, the estimation method of the front-side compensating parameter should be required for accurate estimation of the tsunami force. Moreover, the influence of the property of the rubble mound, which will affect the seepage flow, should be examined in detail.

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