CHAPTER 133

Improvement of Composite Breakwater on Solid Bottom Against Severe Tsunamis

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1. Introduction

Recent diversification in the use of coastal areas has increased the importance of tsunami prevention measures in the areas. To prevent disasters, it is important to set up various facilities, including tsunami breakwaters and tide embankments, and to improve systems to ensure the safety of people escaping from tsunamis with larger waves than predicted when designing the facilities. Previous studies showed that coastal and port structures are effective to decrease damage caused by tsunamis. These structures are, however, easy to overturn or slide, since they are designed without considering tsunamis as external forces on them. The North Breakwater in Okushiri Port damaged by the tsunamis of the Hokkaido Nanseioki Earthquake in 1993 is an example of a damaged composite breakwater (Photo 1).

Recently, a composite breakwater has become popular as a port structure to cope with enlargement of ports and weak ground of coastal areas. It has two tiers: a caisson functioning as an upright breakwater on top, and a mound (rubble-mound foundation) functioning as a sloping breakwater on the bottom. Though a composite breakwater is frequently used as a tsunami breakwater, damage to it by wave forces larger than the external forces predicted for its design has not been sufficiently taken into account. In most cases, an incident wave of a tsunami on the composite breakwater is broken up due to the influence of the water depth,to become a tsunami.Tsunamis have the largest destructive force on a breakwater.

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This study clarifies the features of damage by a surge tsunami to composite breakwaters designed without considering tsunamis as external forces by model experiments.

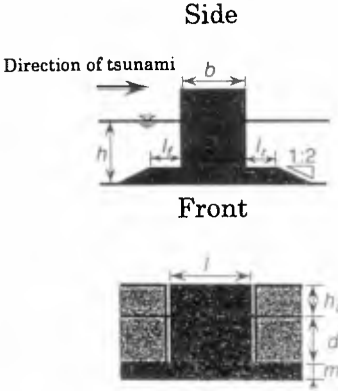
Photo 1 Damaged composite breakwater(1993 Okushiri Port)

2. Dimensional Analysis

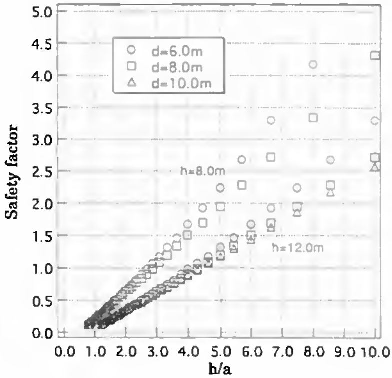
A simple dimensional analysis was made to examine factors influencing the amount of damage to a breakwater Δ (horizontal displacement).

$$\Delta = F\left\{\frac{W'}{\ell\rho ga(d+h_c)},\frac{P_h}{\rho ga(d+h_c)},\frac{P_u}{\rho gab},\frac{\ell_f}{a},\frac{\ell_r}{a},\frac{d}{a},\frac{h}{a},T\sqrt{\frac{a}{g}},f,\ldots\ldots\right\} \qquad (1)$$

where W' = weight in water, P_h = horizontal wave force, P_u = uplift pressure, a = amplitude of a tsunami, T = period of a tsunami, f = friction coefficient. Fig. 1 shows other variables.



Fig–1 Variables



Fig–2 Relationship between Sf and h/a

Generally, Δ depends mainly upon a safety factor of the upright part against sliding. The first term of the right side F in equation (1) is almost equal to the safety factor. In Fig. 2 the axis of ordinates represents the safety factor against sliding and the axis of abscissas represents h/a. The parameters here are the water depth at the upright part (d) and the water depth (h). The wave force was calculated by the wave force formula of a surge tsunami by Tanimoto et al. This figure shows that the safety factor is proportional to h/a and is more influenced by the water depth (h) than the water depth at the upright part (d).

3. Experimental Equipments

3.1 Two-dimensional open channel

In this experiment, a steel two-dimensional open channel (Fig. 3) 15.0 m long, 0.6 m wide and 0.5 m deep was used. The gate was suddenly opend to produce a tsunami. Both sides of the channel were glass and the bottom was steel coated with paint. A gate to adjust the water depth was installed at one end. The breakwater model was placed with its front 3.5 m from the back of the channel. Pipes to adjust the water depth were installed along both side walls of the channel to level the water depths at the front and back of the breakwater. A tsunami was produced by a wave making gate, or a wave paddle, installed at 5.55 m from the breakwater.

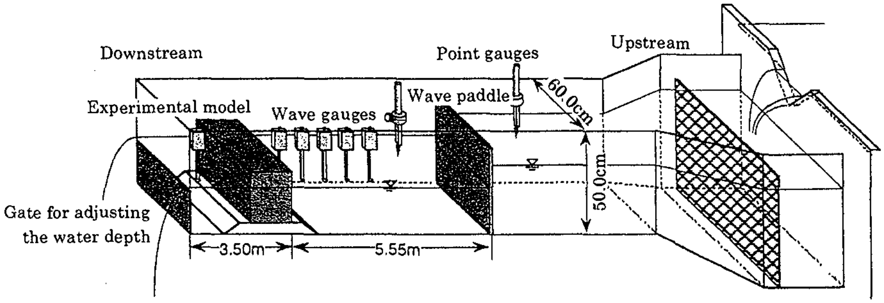


Fig-3 Experimental channel and position of the experimental model

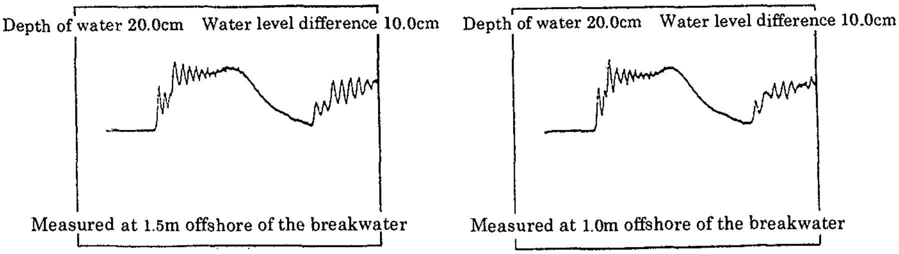
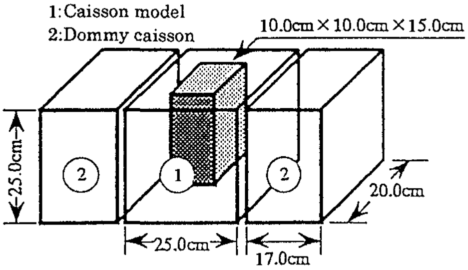


Fig-4 Wave form in the experiment

The difference in the water depths at the front and back of the gate was measured with a point gauge, and the gate was suddenly opened to produce a surge tsunami when the difference reached a specified amount. The installed gate was a wooden, hand–operated vertical lift gate. In this experiment, the difference in the water surfaces at two sides of gate almost corresponded to the amplitude of a surge tsunami. Six capacitance–type wave gauges were installed, and a video camera was installed at the side of the channel to confirm the wave form. Fig. 4 shows examples of wave form in the experiment.

3.2 Experimental model

The experimental model was made from the design of the North Breakwater in Okushiri Port (Photo 1). The North Breakwater in Okushiri Port was constructed recently to increase the calmness in the port located behind the island from the hypocenter. Tsunamis at the time of the earthquake caused foot–protection blocks at the back of the breakwater to drift away; the upright part, especially around the center, overturned and slid; and the mound deformed. The dimensions of a real–size breakwater were assumed from the central part of the North Breakwater which had slid so much. The assumed breakwater was scaled down to 1/40 for the experiments to make a model made of mortar. The dimensions of the assumed breakwater (1/40 figures for each is in brackets) were: height: 10.0 m (25.0 cm); width: 8.0 m (20.0 cm); length: 10.0 m (25.0 cm); height of the mound: 2.0 m (5.0 cm); water depth (h): 8.0 m (20.0 cm). We called the size of the 1/40 model the standard type in this study. The height, width and material of the mound and the water depth (h) were varied during the experiments. And also the weight of the model was varied as an experimental condition, a void of 10.0 cm × 10.0 cm × 15.0 cm (Fig. 5) was made inside the caisson model to make it lighter than reality.



Fig–5 Upright part model

3.3 Mound

The length of the mound was set at the same width of the channel (0.6 m). The standard size of the mound was 5.0 cm in height, 40.0 cm in width, and with the gradient of its slope was 1:2 (standard type). Rubble was used as the mound material, with the equivalent weight of 400 kg (6.0 g for each piece of rubble). Foot–protection blocks placed on the surface of the mound were ignored. By assuming that the mound was a sloping breakwater, the stability number and the Reynolds number of the surface layer of the sloping breakwater were calculated to investigate the mounds stability and scale effect. As a result, we found that the scale effect need not to be considered and that the stability number was larger than that of the sloping breakwater, in spite of the low critical wave height for stability. From these findings, the weight and the size of the rubble seemed to be sufficient. Also, the experimental result that the rubble of the mound at the front of the breakwater did not move corresponded to the theory that rubble does not move. The reason why the rubble of the mound at the back of the breakwater moved seemed to be due to sliding of the upright part.

4. Experimental Procedure

The experiments were designed to investigate the behavior of the breakwater sliding (the sliding distance which is defined as the distance of the horizontal movement of its upright part), when receiving a surge tsunami produced at a specified water level difference. Tsunami amplitude was increased by 1.0cm, untill all number of times became fatal damage. However the results varied much depending on the conditions of the mound and the breakwater. To understand the trend of the results of the experiments, a wave was produced 10 times for each amplitude. If a sliding distance of the caisson model exceeded 20.0 cm, the effect on the breakwater was different from the expected one. We called this effect on the breakwater fatal damage, and only the number of times was counted.

4.1 Effect of the water depth

Influenced by astronomical tides, storm surges and wind waves, the actual water level varies from the standard water level when an incident wave acts on a breakwater. In this experiment, therefore, we investigated the behavior of the upright part and the damage to the mound part, when the breakwater model and the mound had the standard type, and only the water depth (h) was varied from 16.0 cm to 24.0 cm.

4.2 Effect of the configuration of the mound

Composite breakwaters have varied shapes according to the design conditions, including the water depth (h), the design wave, and the purpose of the installment. This experiment, therefore, was designed to see how the damage of the breakwater was affected by changes in the height and width of the mound.

(1) Height

This experiment determined the behavior of the breakwater, when the water depth at the upright part (d) was constant(15cm) and the height of the mound was 5.0 cm, 7.0 cm, and 9.0 cm.

(2) Width

This experiment determined the changes in the behavior of the breakwater, when the width of the mound was increased by 10.0 cm from the standard type.

4.3 Effect of the weight of breakwater

A general and popular way to increase the stability of the breakwater against wave forces is to increase its weight. This method is effective for waves smaller than the design waves. However, its effectiveness for tsunamis larger than the design waves has not been clarified. This experiment investigated changes in the damage, when a weight was placed on the breakwater.

4.4 Effect of W'

In the experiment where the water depth was changed, the results were difficult to interpret due to the changes in buoyancy and wave forces caused by the changing water depth. In this experiment, the weight offsetting the increased buoyancy caused by the changing water depth was placed on the breakwater to keep constant the underwater weight. The experiment aimed to understand the changes in the behavior due to changes in wave forces.

4.5 Effect of the restraining the settlement of breakwater

Previous experiments showed that fatal damage of the breakwater and its settlement often happend at the same time. We considered that a reinforced mound could be effective to prevent damage by tsunamis. Damage was investigated after installing supporting rods in the mound under the back of the breakwater to restraining the breakwater settlement (Fig. 6).

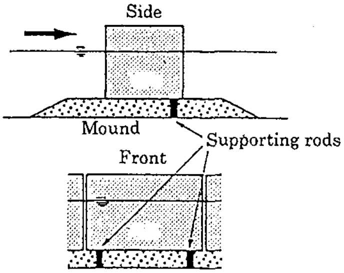


Fig-6 Effect of restraining the settlement of breakwater

5. Results and Discussion

5.1 Effect of the water depth (Fig. 7)

To understand the basic trend, the standard type for this experiment with the water depth at 20.0 cm (c) was investigated. As tsunami amplitude increased, the sliding distance and the number of cases of fatal damage increased, though the results were partly contradictory. When tsunami amplitude was 8.0 cm or less, the breakwater did not slide, and when it was 14.0 cm or more, the breakwater always underwent fatal damage. The sliding distances varied less when the amplitude was close to 7.0 cm or to 16.0 cm, and they varied more when the amplitude was halfway between these two distances. Such a wide variation in sliding distances halfway between 7.0 cm and 16.0 cm seemed to be caused by all the manual operations, including molding the mound and installing the caisson model.

We found that, in general, the deeper was the water depth, the easier the breakwater slid. The number of cases of complete fatal damage increased almost in proportion to the increase in the water depth. It means that as the water depth increased, the influence from front wave pressure and buoyancy increase.

5.2 Effect of the configuration of the mound

(1) Height (Fig. 8)

Fig. 8 (a) shows the experimental results of the mound in the standard type with the water depth at 20.0 cm. As the mound height increased, the number of cases of fatal damage increased compared to the standard type. This trend was particularly obvious when the mound was 9.0 cm high, because the higher mounds seemed to have less stability and tended to fall down on a large scale when the breakwater began to slide. The critical point of sliding in terms of the tsunami amplitude was irrelevant to the height of the mound, because the constant water depth in front of the breakwater contributed to maintaining the same wave pressure on the breakwater front. The tendency for shorter sliding distances for the mound 7.0 cm high than those for the mound 5.0 cm high (standard type) was considered to be due to experimental errors from different experimental conditions.

(2) Width (Fig. 9)

Wider mounds brought better stability. No fatal damage was recorded especially when the mound was extended 10 cm toward the rear, though the sliding distance increased due to the shorter front side of the mound. This must be because more energy was required for the sliding while the mound at the rearside of the breakwater was settling.

5.3 Experiment of the weight of breakwater (Fig. 10)

Fig. 10 (a) is the standard type, with the weight of the breakwater of the standard weight +0.0 kg. When the tsunami amplitude was the same, as the weight increased the sliding distance decreased, because a larger horizontal wave force was required for sliding as the weight increased. However, when the weight was +3.0 kg, the breakwater had fatal damage at tsunami amplitude of 12.0 cm and the sliding distance was fairly large, because the bearing capacity of the mound did not sufficiently accommodate the increase in the vertical load. Therefore, once the mound starts to fall down, it falls down completely to the solid bottom of channel. The results of this experiment cannot be simply compared to the other results, since the installment conditions of the breakwater in this experiment were slightly different from those of the others.

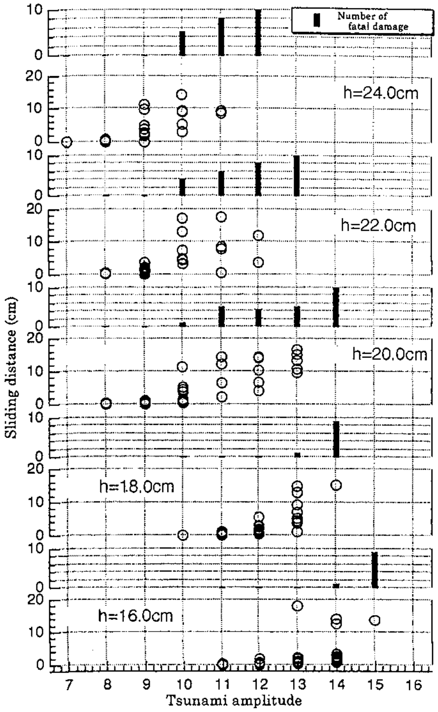


Fig-7 Effect of the water depth

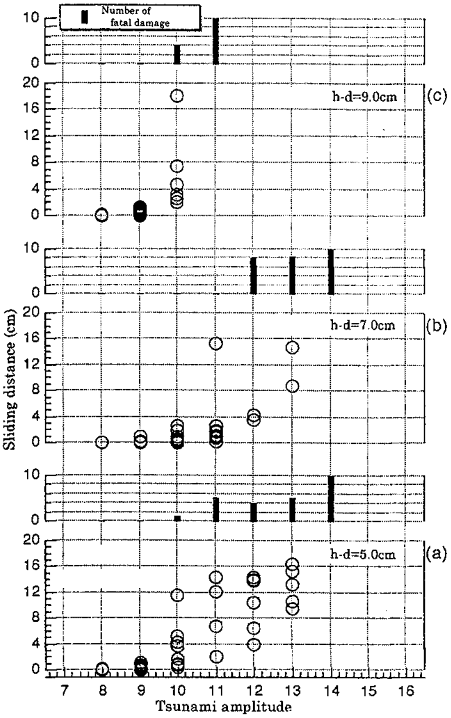
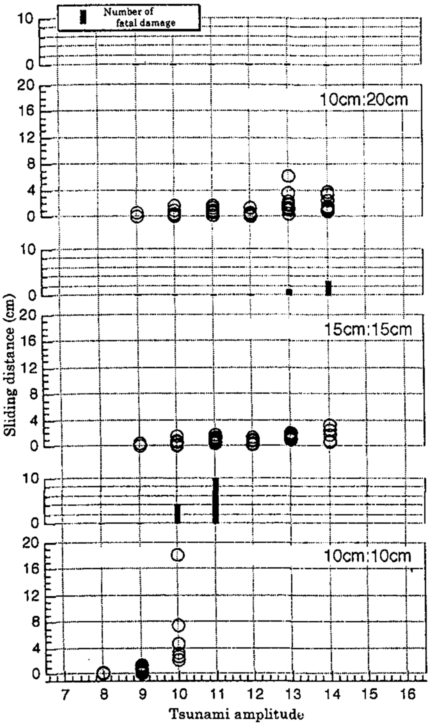
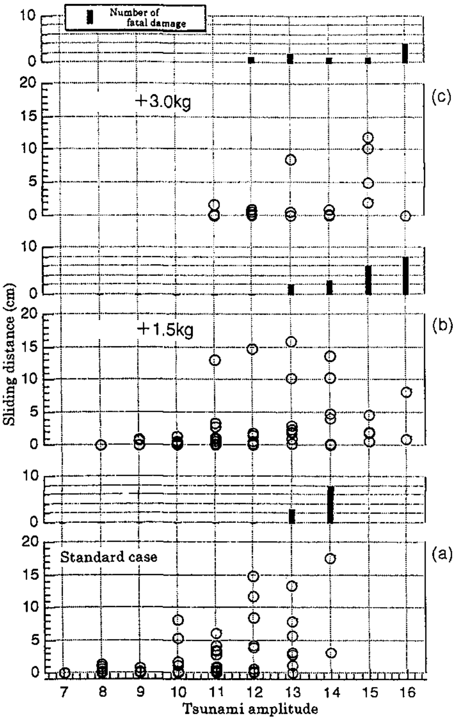


Fig-8 Effect of the mound height



Fig–9 Effect of the mound width



Fig–10 Effect of the weight of breakwater

5.4 Effect of W' (Fig. 11)

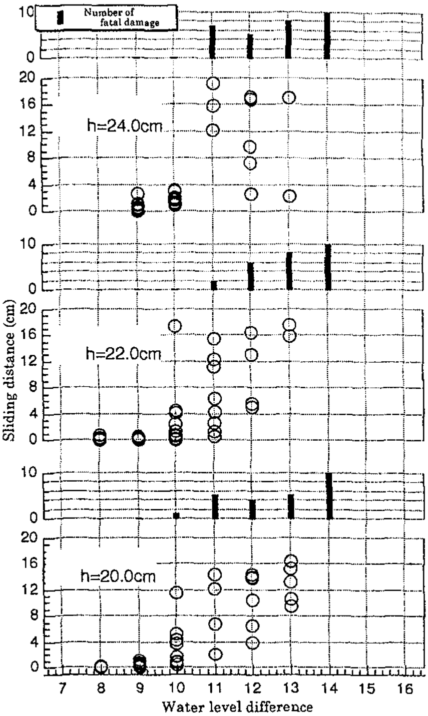
Fig. 11 (a) shows the standard type. Breakwater with a weight on top slid less, in the same way as in the experiment by changing the weight. The critical point of sliding for each case was mostly the same. Also, the trend towards fatal damage and the tsunami amplitude causing fatal damage were almost the same. As a result, we found that buoyancy change had a greater influence than the change in wave force caused by the water depth change.

5.5 Effect of restraining the settlement of breakwater (Fig. 12)

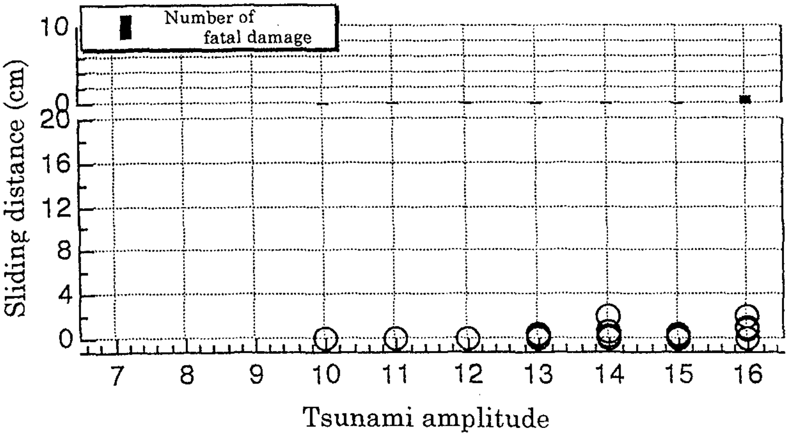
This experiment shows the least sliding distance and the least number of cases of fatal damage, compared to other experiments, because the falling down of the mound was restrained by supporting the breakwater. This means that the stability of the mound was dominant in influencing the sliding distance of the breakwater.

5.6 Features of Damage

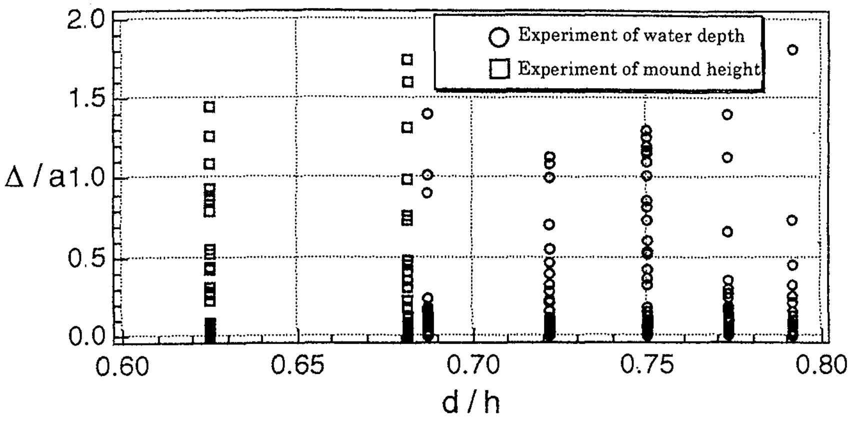
Fig. 13 is from the data of the experiments on the water depth and the mound height. The axis of abscissas represents the water depth at the breakwater divided by the water depth, and the axis of ordinates represents the sliding distance divided by the water level difference producing a tsunami. Each figure is non-dimensional. Within the region of these experiments, the figures on the axis of ordinates did not exceed 2.0 unless the breakwater had fatal damage. This shows that the sliding distance was under twice the tsunami amplitude. The results corresponded to those of the experiment by changing the width of the mound, where the mound was moved toward the rearside. Moving toward both edges of the axis of d/h indicates the breakwater became less stable and easier to slide or have fatal damage, but near the axis center indicates the breakwater was most resistive to slide. As a result, the breakwater with d/h around 0.7 appears to be the most stable.



Fig–11 Effect of W'



Fig–12 Effect of the restraining settlement of breakwater



Fig–13 Features of damage

6. Conclusion

This study aimed to clarify the features of damage of a composite breakwater by tsunamis through experiments, and to find better damage prevention measures. As a result of this study, the following have been clarified.

6.1 Effect of breakwater configuration

1) An increase in buoyancy was more responsible for damage than an increase in wave pressure on the front of the breakwater due to the increase in the water depth.

2) Stability against sliding was remarkably influenced by the mound conditions. The stability increased, especially when the mound was prolonged toward the rear and when the mound was reinforced with body supporting rods.

3) A heavier weight of a breakwater for stabilizing the breakwater or an unnecessarily higher mound was not advisable, since it was easier to have fatal damage when exceeding the critical values.

4) For stability of a breakwater , the desirable ratio of the water depth (h) and the water depth at the upright part (d) was when the d/h ratio was around 0.7.

6.2 Proposed stability criteria

Stability criteria of composite breakwaters against tsunami wave action are deduced from the experimental result employing a dimensionless displacement, as,

Heavy Damage $\Delta/a > 1.0$ for $\mu W_u' / Ph \leqq 1.0$
Slight Damage $\Delta/a < 0.1$ for $\mu W_u' / Ph \geqq 2.0$

where a is tsunami amplitude, μ is the friction coefficient between the upright structure and the mound, W_u' ($=W' / \ell$)is weight of upper structure per unit length in water and Ph is the horizontal tsunami wave force per unit length. (Fig. 14)

6.3 Countermeasures

1)To increase simply the weight of upper structure is effective to the critical tsunami height, but Δ becomes abruptly greater for the tsunamis higher than it.

2)Prolongation of the rear shoulder ℓr is effective to lessen Δ to prevend the earlier falling down.

3)Most effective way to decrease Δ is to strengthen the mound surface around the heel of upright structure since Δ gradually becomes large as the stress concentration near the heel proceeds during the tsunami colliding on upright structure.

7. Acknowledgement

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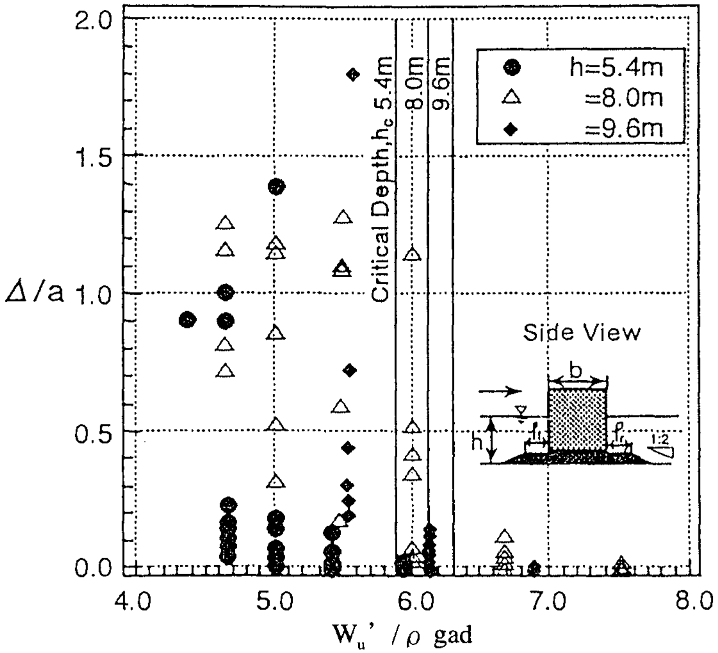

Fig-14 Dimensionless displacement of caisson by model tsunami