

# Wave Force on Coastal Dike due to Tsunami

by

Fuminori Kato<sup>1</sup>, Shigeki Inagaki<sup>2</sup> and Masaya Fukuhama<sup>3</sup>

## ABSTRACT

This paper presents results of large-scale experiments on wave force due to tsunami. A model of coastal dike was installed in a wave channel of 140 m long, 5 m deep, and 2 m wide. Wave pressure on the dike, and wave height and current velocity around the dike were measured during the runup of solitary wave. Wave breaking of the solitary wave on the beach caused impulsive wave pressure on the offshore slope of the dike. Applicability of wave pressure formulas to the coastal dike was evaluated.

**KEYWORDS:** Coastal Dike, Model Experiment, Tsunami, Wave Force, Wave Pressure

## 1. INTRODUCTION

In Japan, dike has been built along the coast to guard coastal area from tsunamis, storm surges and high waves. Coastal dike prevents tsunami from infiltrating to the hinterland, although tsunami heights expected for earthquakes in the near future are larger than height of coastal dike in some area. Damage by tsunami should be comprehensively estimated for disaster management, as shown in Fig. 1.

Coastal dike should be stable against tsunami runup to minimize damage in the hinterland. Wave force induced by tsunami is one of the factors related to failure of coastal dike. In shallow water, tsunamis sometimes make several bores and cause impulsive force on structures, which can't be easily simulated in numerical calculations.

In the past studies, wave force acting on offshore structures or onshore structures was evaluated through model experiments in which the structures were installed on the level bed. Since coastal dike is usually built behind a sloping beach, wave force on coastal dike

should be evaluated in consideration of tsunami transformation on the slope. Beside this, an upright wall was usually used as a model of the structures in the past studies, while seaward slope of coastal dike is not always upright. Therefore, results of the past experiment with an upright wall can't be applied for sloping dike without some examination.

To evaluate wave force on coastal dike caused by tsunami, we conducted a series of large-scale experiment on wave pressure, taking wave transformation and dike slope into account.

## 2. EXPERIMENTAL SETUP

As shown in Fig. 2, a fixed bed (slope: offshore 1/20, onshore 1/100) was built in a wave channel (length: 140 m, depth: 5 m, width: 2 m) of National Institute for Land and Infrastructure Management, Japan. The channel is equipped with a piston-type wave-maker driven by a large servomotor. The wave-maker can produce solitary wave of up to 0.4 m high. 5 types of coastal dike (scale: around 1/10) were installed on the bed as shown in Table 1. The dike of type 1-4 completely divided the channel. To measure wave pressure near the edge of the dike, the type 5 dike of 1 m wide was placed as shown in Fig. 3

As illustrated in Fig. 4, 23 pressure gages were stuck on the seaward slope, the crest and the landward slope of the coastal dike, and the bed behind the dike at intervals of 10 cm. We numbered the gages from the seaward. As for type 5, we concentrated the pressure gages near the edge of the dike as shown in Fig. 3. 8 wave gages and 6 current meters were also arranged.

---

<sup>1</sup> Senior Researcher, Coast Division, River Research Department, National Institute for Land and Infrastructure Management, Tsukuba-shi, Ibaraki-ken 305-0804 Japan

<sup>2</sup> Guest Researcher, ditto

<sup>3</sup> Head, ditto

Sampling interval of the pressure gages was set at 0.002 s according to Mizutani and Imamura (2000).

Table 2 shows hydraulic conditions of the experiments. To take effects of beach on wave transformation into account, 5 water levels and 3 wave heights were combined.

### 3. RESULTS OF EXPERIMENTS

#### 3.1 Process of Wave Runup

Fig. 5 shows temporal variations of water level, current velocity, and wave pressure in the case when the shoreline was at the toe of the type 3 dike. H4 and H5 correspond to water levels at the toe of the seaward slope and the top of the seaward slope, respectively. V5 is current velocity at the top of the seaward slope. P1, P3 and P5 correspond to wave pressures at the toe of the seaward slope, 0.2 m above the toe of the seaward slope, and 0.4 m above the toe of the seaward slope, respectively. Wave height, which was 0.4 m offshore, increased to 1.1 m at H4 and 0.6 m at H5 in 1 second. After that, water levels decreased to 0 in 12 seconds at H4, and in 6 seconds at H5. Current velocity at V5 exceeded 2 m/s before the peak of the water level at H5. Wave pressure at P3 reached the peak exceeding  $500 \text{ gf/cm}^2$  (49.0 kPa) just after the wave arrival. After that, it slowly fluctuated around  $100 \text{ gf/cm}^2$  (9.8 kPa). The peak of the wave pressure remained for only 0.004 s as shown in Fig. 6, an enlargement of the temporal variation of P3 in Fig. 5. The similar temporal variation was observed also in many cases.

#### 3.2 The Maximum Wave Pressure

As explained above, the peak of wave pressure was often impulsive. As a representative value, the maximum wave pressure at each point was extracted for the cases that height of incident wave was 0.4 m, and plotted in figures 7-11.

##### 3.2.1 Type 1

Fig. 7 shows the maximum wave pressure for type 1. In the case when the shoreline was at the toe of seaward slope (T1pm0 in Fig. 7), the maximum wave pressure at P2 (0.1 m above the toe of seaward slope) was about  $400 \text{ gf/cm}^2$

(39.2 kPa), the largest among all points. In this case, water collided with the dike after wave breaking off the dike as shown in Photo 1. Also in the case when water level was 0.15 m lower than T1pm0 (T1m15 in Fig. 7), bore induced after wave breaking ran up on the seaward slope, resulting that the maximum wave pressure at P1 (the toe of seaward slope) reached  $300 \text{ gf/cm}^2$  (29.4 kPa). In the other cases, the maximum wave pressure on the seaward slope was less than  $100 \text{ gf/cm}^2$  (9.8 kPa).

From the upper part of the seaward slope to the center of the landward slope, the maximum wave pressure was smaller than  $100 \text{ gf/cm}^2$  (9.8 kPa) in any water level conditions. But from the lower part of the landward slope, the maximum wave pressure obviously increased and peaked at P22 (0.4 m inland the toe of the landward slope) except low water level conditions.

##### 3.2.2 Type 2

As shown in Fig. 8, the maximum wave pressure on the seaward slope for type 2 was lower than that for type 1 in the case that the shoreline was at the toe of the seaward slope (T2pm0 in Fig. 8), although the gradient of the offshore slope was the same between the two dikes. It implies that small difference in incident wave height may change distribution of wave pressure on the slope. On the other hand, the tendency that the maximum wave pressure behind the dike was larger than that on the crest and the landward slope was the same as type 1. But the location of the peak pressure behind the dike was closer to the dike than that for type 1, because of the difference in gradient of the landward slope.

##### 3.2.3 Type 3

In the case when the shoreline was at the toe of the seaward slope (T3pm0 in Fig. 9), the maximum wave pressure exceeded  $500 \text{ gf/cm}^2$  (49.0 kPa) at P3 (0.2 m above the toe of the seaward slope) and P4 (0.3 m above the toe of the seaward slope), and  $200 \text{ gf/cm}^2$  (19.6 kPa) at P6 (the top of the seaward slope). In the case that water level was 0.15 m lower than T3pm0 (T3m15 in Fig. 9), wave broke more offshore than T3pm0, resulting that the maximum wave pressure at the toe of the seaward slope was less

than 140 gf/cm<sup>2</sup> (13.7 kPa) and smaller than those for type 1 and type 2. In contrast, in the case that water level was 0.15 m higher than T3pm0 (T3p15 in Fig. 9), the maximum wave pressure was relatively large at P6 (the top of the seaward slope) because breaking wave strongly collided with the upper part of the seaward slope as shown in Photo 3.

The maximum wave pressure was relatively small from the crest to the center of the landward slope, and around 100 gf/cm<sup>2</sup> (9.8 kPa) behind the toe of the landward slope.

### 3.2.4 Type 4

As shown in Fig. 10, distribution of the maximum wave pressure on the seaward slope was similar to that for type 3. The maximum wave pressure was very large at P3 (0.2 m above the toe of the seaward slope) and P4 (0.3 m above the toe of the seaward slope) in the case when the shoreline was at the toe of the seaward slope (T4pm0 in Fig. 10). As for the bed behind the dike, the maximum wave pressure at P18 (the toe of the landward slope) was relatively large, as same as type 2.

### 3.2.5 Type 5

Fig. 11 illustrates the relation between the maximum wave pressure on the side wall and the maximum water depth. Unlike Figures 7-10, data measured in the case with incident wave height of 0.3 m also included in the plots. The solid line in the figure corresponds to hydrostatic pressure on the bed. Different from the seaward slope, the maximum wave pressure on the side wall was not so larger than the hydrostatic pressure on the bed.

Fig. 12 shows the maximum wave pressure at the edge of the dike in the case that the shoreline was at the toe of the seaward slope. Compared with type 3 (seaward slope in Fig. 12), the pressure at the edge of the seaward slope was very small in lower part. The pressure on the side wall was much smaller than that on the seaward slope. These results indicate that wave pressure at the edge of the seaward slope doesn't exceed that on the seaward slope much, and that wave pressure on the side wall is much smaller

than that on the seaward slope.

## 4. DISCUSSION

### 4.1 Wave Pressure on Seaward Slope

Tanimoto et al. (1984) performed large-scale experiment on an upright breakwater using a sine wave, and proposed formulas to estimate wave pressure as follows.

$$p_m(z')/\rho g a_H = 2.2(1 - z'/3a_H) \quad (0 \leq z'/a_H \leq 3) \quad (1)$$

$$p_m(z')/\rho g a_H = 2.2 \quad (z'/a_H \leq 0) \quad (2)$$

where  $p_m$  is the maximum wave pressure,  $z'$  is the height from the still water level,  $a_H$  is the amplitude of wave,  $\rho$  is the water density, and  $g$  is the acceleration of gravity.

Ikeno et al. (2001) conducted model experiment on bore like tsunami colliding an offshore upright wall, and introduced the extra coefficient  $\alpha$  for wave breaking into the formulas proposed by Tanimoto et al. (1984).

$$p_m(z')/\rho g a_H = 2.2(1 - z'/3a_H)\alpha \quad (0 \leq z'/a_H \leq 3) \quad (3)$$

$$p_m(z')/\rho g a_H = 2.2\alpha \quad (z'/a_H \leq 0) \quad (4)$$

$$\alpha = 1.36 \quad (0 \leq z'/a_H \leq 3) \quad (5)$$

$$\alpha = 1.36(1 + 0.52z'/a_H) \quad (-0.5 \leq z'/a_H \leq 0) \quad (6)$$

$$\alpha = 1.0 \quad (z'/a_H \leq -0.5) \quad (7)$$

Ikeno et al. (2003) performed model experiment on bore like tsunami attacking an onshore upright wall, and improved the formulas of Ikeno et al. (2001). The improved formulas give larger pressure around the still water level.

$$p_m(z')/\rho g a_H = 3 - z'/a_H \quad (0.5 \leq z'/a_H \leq 3) \quad (8)$$

$$p_m(z')/\rho g a_H = 4 - 3z'/a_H \quad (0 \leq z'/a_H \leq 0.5) \quad (9)$$

$$\frac{p_m(z')}{\rho g a_H} = 4 + 3.6z'/a_H \quad (-0.5 \leq z'/a_H \leq 0) \quad (10)$$

$$\frac{p_m(z')}{\rho g a_H} = 2.2 \quad (z'/a_H \leq -0.5) \quad (11)$$

Figures 13 and 14 show vertical distribution of the maximum wave pressure on the seaward slope. The vertical axis in the figures is height from the still water level normalized by wave height at the toe of the seaward slope. Plots are results of this study, and lines correspond to the equations mentioned previously. In case that the gradient of the seaward slope was 1:1, most of the measured pressures were lower than those calculated by Tanimoto et al. (1984), and the formulas by Ikeno et al. (2003) didn't underestimate measured wave pressure. On the other hand, in case that the gradient of the seaward slope was 1:0.5, even the formulas by Ikeno et al. (2003) underestimated measured wave pressure, especially in cases that the shoreline was at the toe of the seaward slope.

#### 4.2 Wave Pressure on Landward Slope and behind the Dike

Mizutani and Imamura (2002) carried out model experiment on bore overflowing a dike on level bed, and proposed the following equations to calculate the maximum wave pressure behind a dike:

$$\frac{p_{om}}{\rho g H_{d2}} = 2\sqrt{2} \frac{V_m \sin \theta_2}{\sqrt{g H_{d2}}} \quad (12)$$

$$\frac{p_{om}}{\rho g H_{d2}} = \left( 2\sqrt{2} \frac{V_m \sin \theta_2}{\sqrt{g H_{d2}}} \right)^4 \quad (13)$$

where  $p_{om}$  is the maximum overflowing wave pressure,  $V_m$  is the maximum velocity on the dike crest,  $\theta_2$  is the angle of the landward slope, and  $H_{d2}$  is the height of dike crest. Equation (12) gives overflowing pressure, and impact overflowing pressure calculated with equation (13) can occur under the following condition:

$$2\sqrt{2} \frac{V_m \sin \theta_2}{\sqrt{g H_{d2}}} \geq 1 \quad (14)$$

Fig.15 shows measured pressures as well as values calculated with equations (12) and (13). The measured pressures didn't exceed the calculated values. It indicates that the equations can be applied for the experiment with solitary waves.

## 5. CONCLUSIONS

By conducting a series of large-scale experiment, distribution of wave pressure on coastal dike was revealed. Wave breaking in front of coastal dike caused impulsive wave pressure in the lower part of the seaward slope. In the case that gradient of the seaward slope was 1:0.5, breaking wave collided to the upper part of the seaward slope, and gave large wave pressure there. The maximum wave pressure on the seaward slope was larger than those given by the formulas of Ikeno et al. (2003) in some cases that the shoreline was located at the toe of the seaward slope. It was confirmed that the formulas of Mizutani and Imamura (2002) on overflowing wave pressure could be applied to this experiment with solitary wave. The maximum wave pressure on the side wall slightly exceeded hydrostatic water pressure on the bed at most.

## 6. ACKNOWLEDGEMENTS

We thank Mr. Sato and Mr. Yamada of INA for their efforts on the experiments.

## 7. REFERENCES

1. Ikeno, M., Mori, N. and Tanaka, H.: Experimental Study on Tsunami Force and Impulsive Force by a Drifter under Breaking Bore like Tsunamis, *Proceedings of Coastal Engineering*, JSCE, Vol.48, 2001.
2. Ikeno, M. and Tanaka H.: Experimental Study on Impulse Force of Drift Body and Tsunami Running up to Land, *Proceedings of Coastal Engineering*, JSCE, Vol.50, 2003.
3. Tanimoto, K., Tsuruya, K. and Nakano, S.: Tsunami Force of Nihonkai-Chubu

Earthquake in 1983 and Cause of Revetment Damage, *Proceedings of the 31th Japanese Conference on Coastal Engineering*, JSCE, 1984.

4. Mizutani, S. and Imamura, F.: Hydraulic Experimental Study on Wave Force of a Bore Acting on a Structure, *Proceedings of*

*Coastal Engineering*, JSCE, Vol.47, 2000.

5. Mizutani, S. and Imamura, F.: Design of Coastal Structure Including the Impact and Overflow on Tsunamis, *Proceedings of Coastal Engineering*, JSCE, Vol.49, 2002.

Table 1 Dike Model

Type	Width (m)	Seaward slope	Landward slope
1	2	1:1	1:1
2	2	1:1	1:1.5
3	2	1:0.5	1:1
4	2	1:0.5	1:1.5
5	1	1:0.5	1:1

Table 2 Hydraulic Conditions

Type	Water level (m)	Height of incident wave (m)	Remark
1-4	3.50 (m30)	0.2	15 cases for each type
	3.65 (m15)		
	3.80 (pm0)		
	3.95 (p15)		
	4.10 (p30)		
5	3.80	0.4	
	3.95	0.3	
	3.95	0.4	

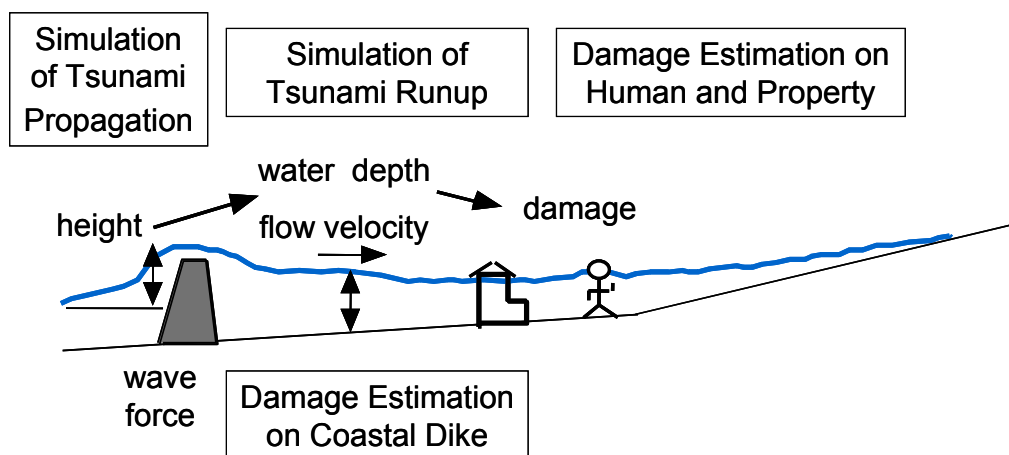


Fig.1 Comprehensive Damage Estimation on Tsunami Disaster

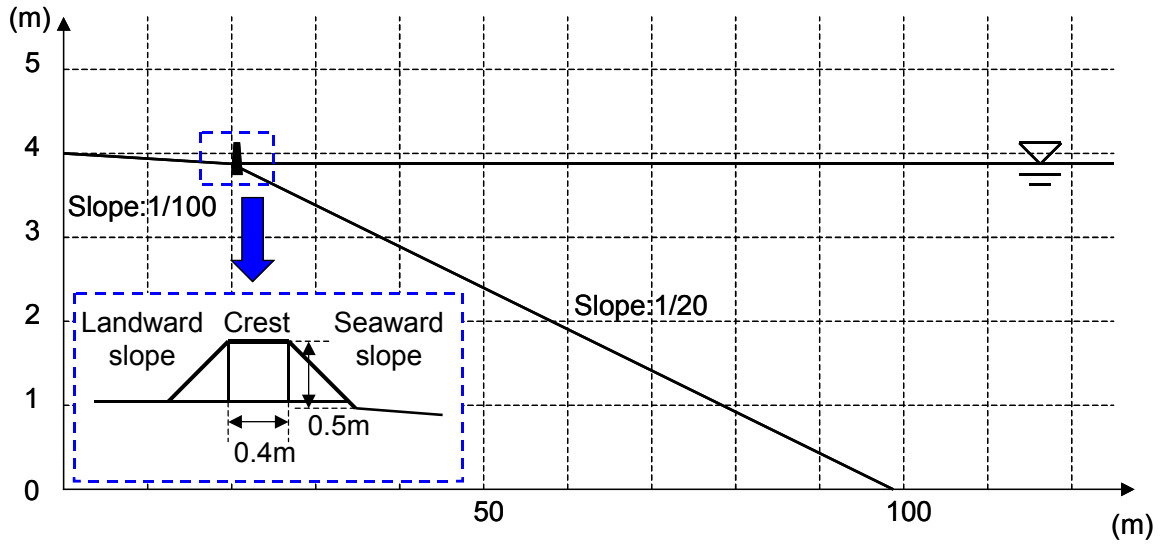


Fig.2 Schematic View of Experimental Setup

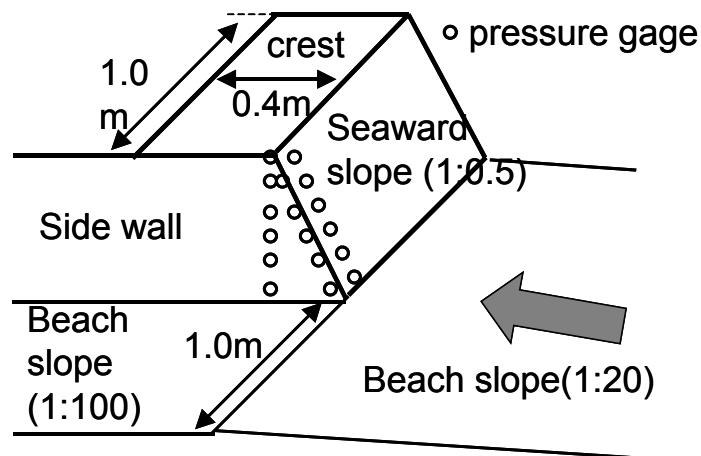


Fig.3 Dike Model Setup (Type 5)

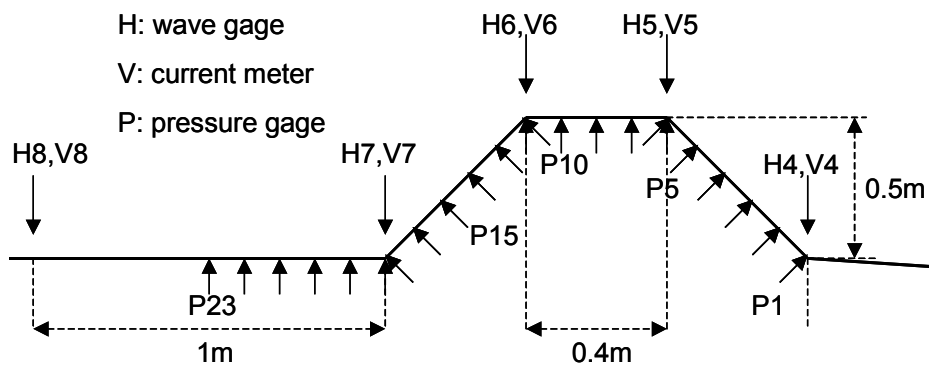


Fig.4 Arrangement of Gages (Type 1-4)

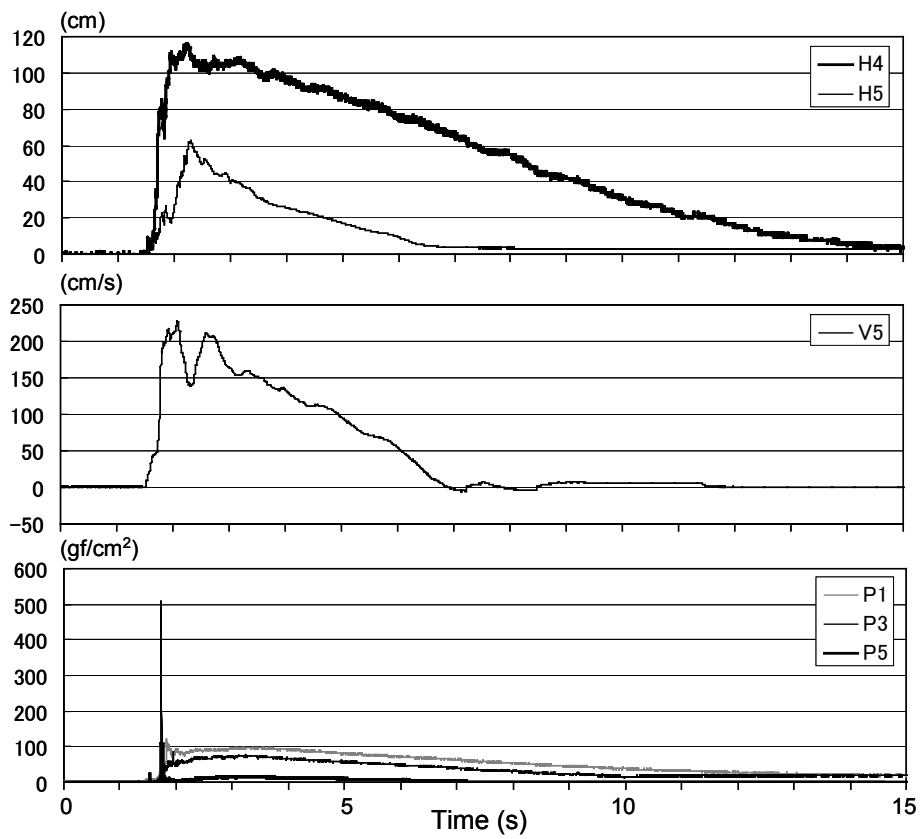


Fig.5 Temporal Variations of Water Level, Current Velocity and Wave Pressure (T3pm0)

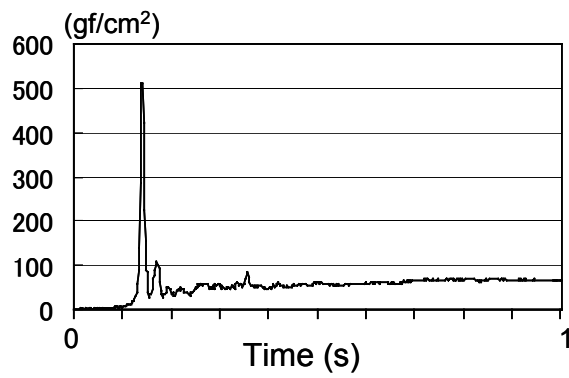


Fig.6 Temporal Variation of Wave Pressure near the Peak (T3pm0)

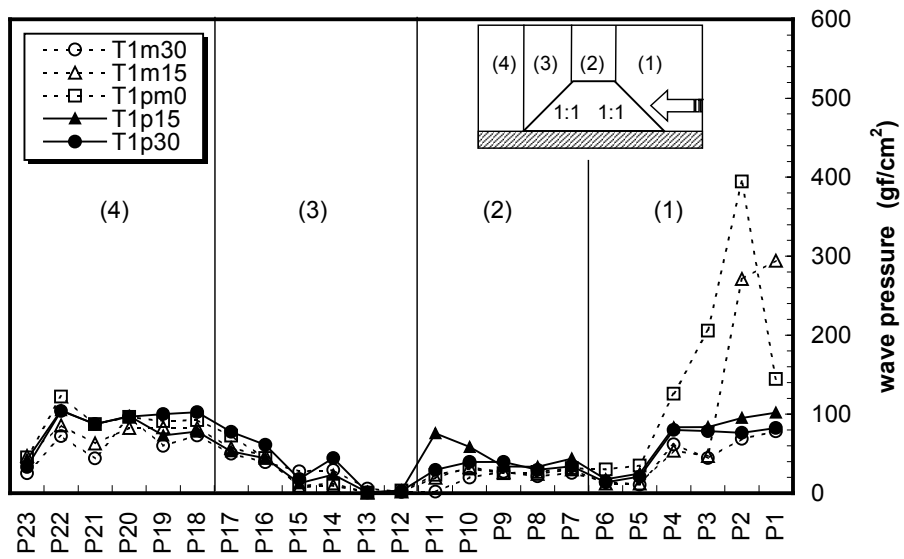


Fig.7 Maximum Wave Pressure (Type 1)

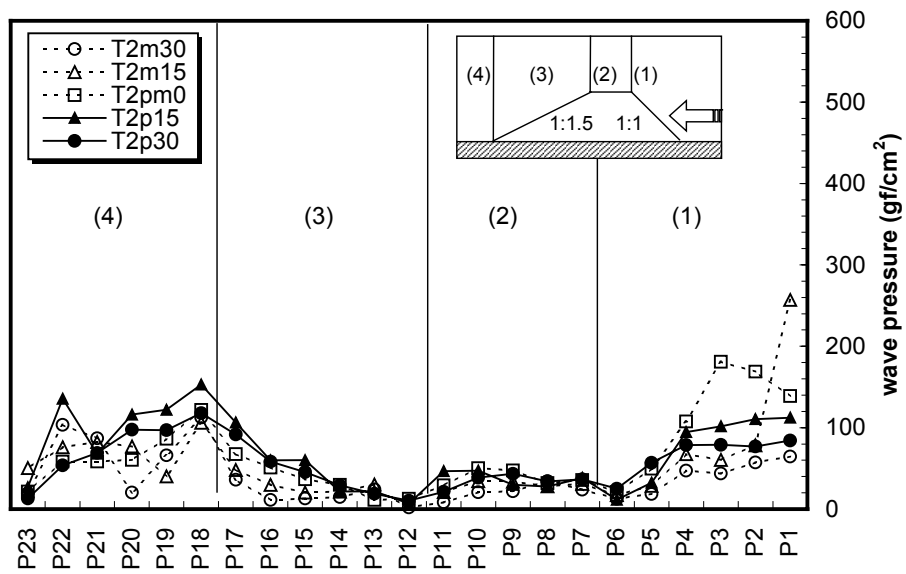


Fig.8 Maximum Wave Pressure (Type 2)



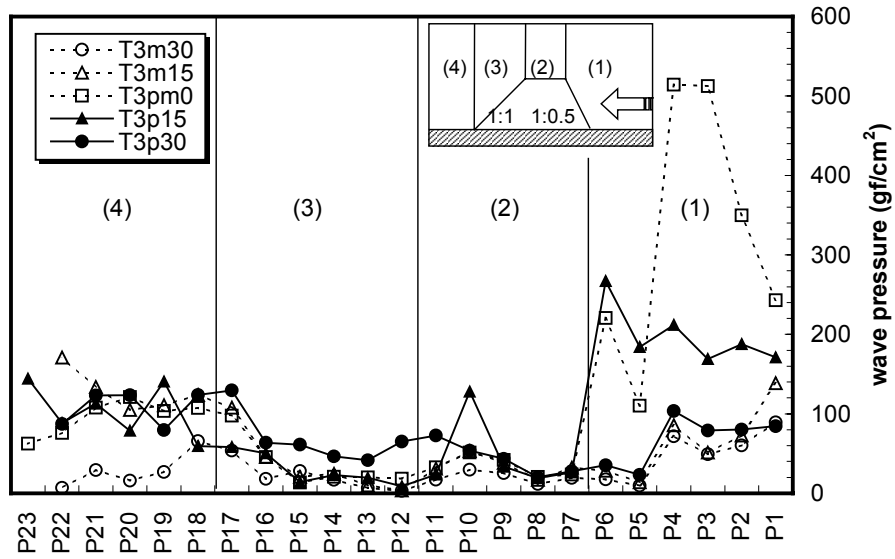


Fig.9 Maximum Wave Pressure (Type 3)

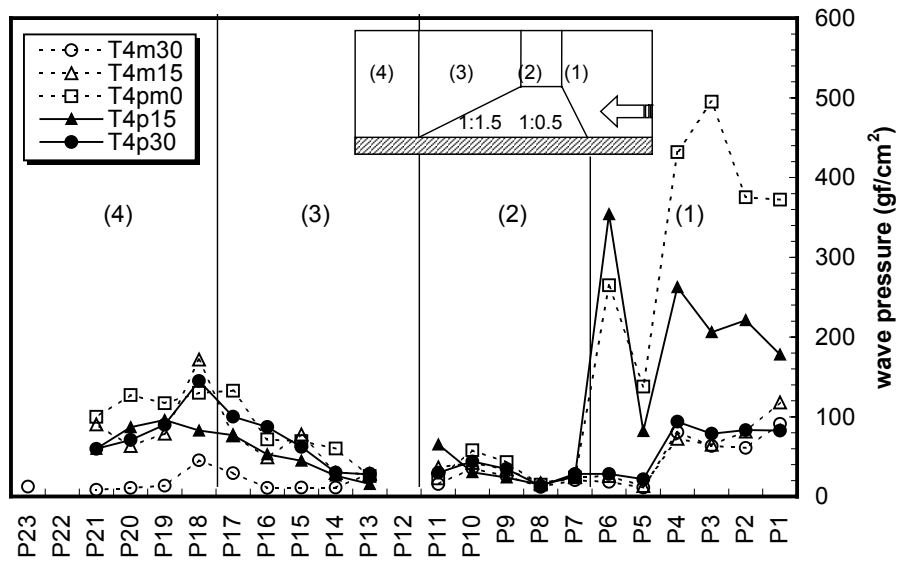


Fig.10 Maximum Wave Pressure (Type 4)

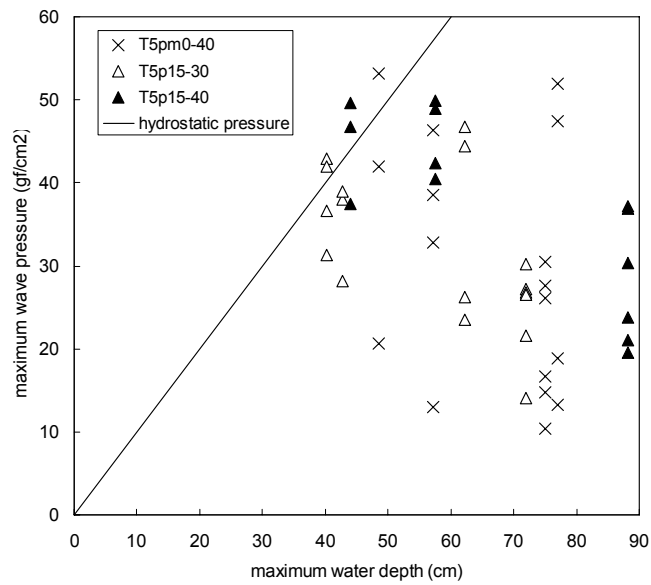


Fig.11 The Maximum Wave Pressure on the Side Wall and the Maximum Water Depth (Type 5)

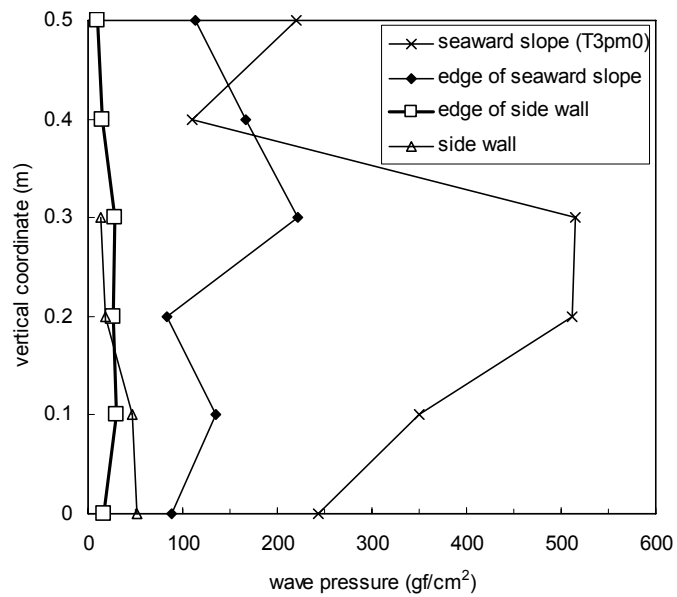


Fig.12 The Maximum Wave Pressure on the Edge (Type5, Water Level 3.8m, Wave Height 0.4m)

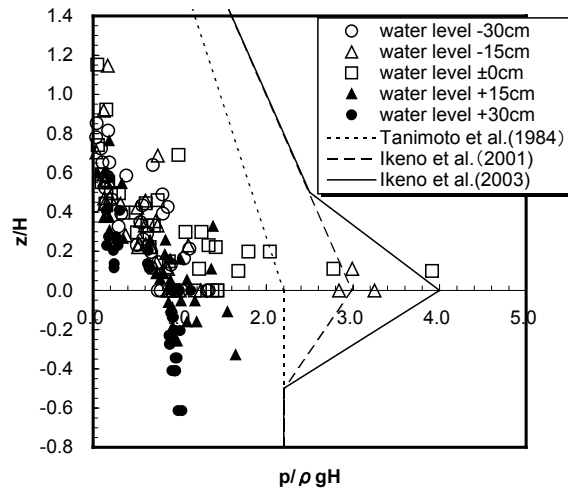


Fig.13 Vertical Distribution of the Maximum Wave Pressure (Type 1-2, Seaward Slope 1:1)

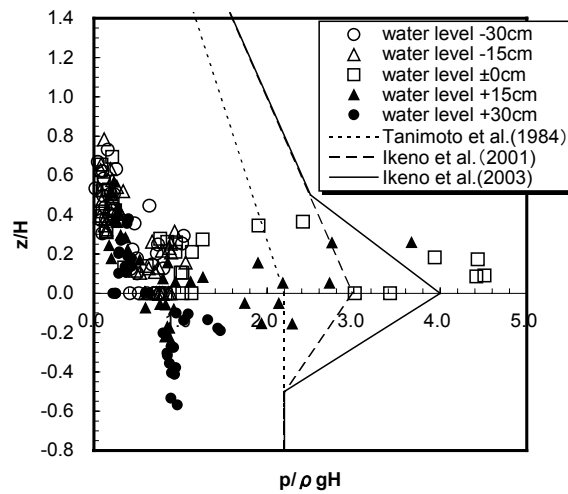


Fig.14 Vertical Distribution of the Maximum Wave Pressure (Type 3-4, Seaward Slope 1:0.5)

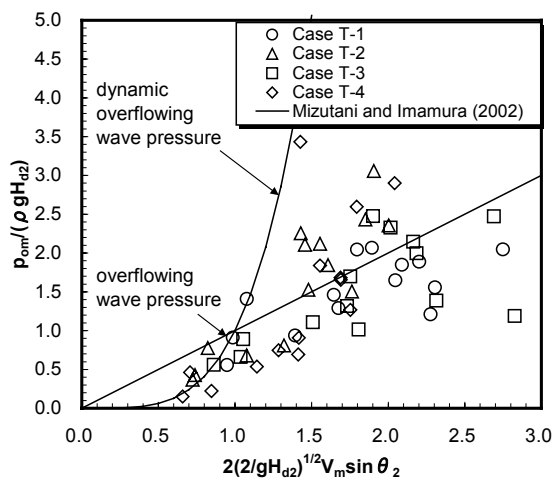


Fig.15 The Maximum Overflowing Wave Pressure (Type 1-4)

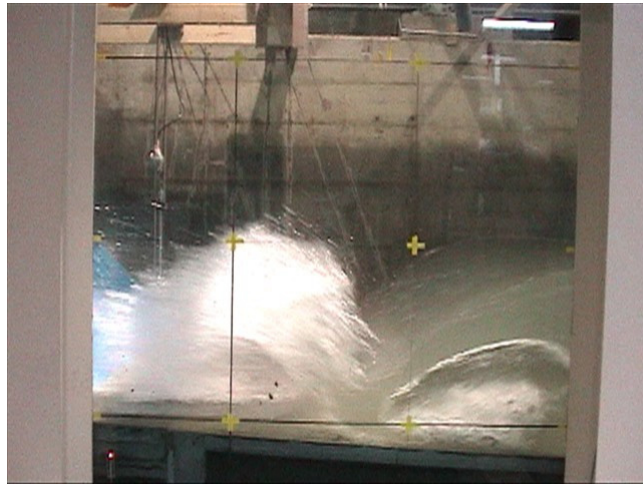


Photo 1 Wave Breaking off the Dike (T1pm0)

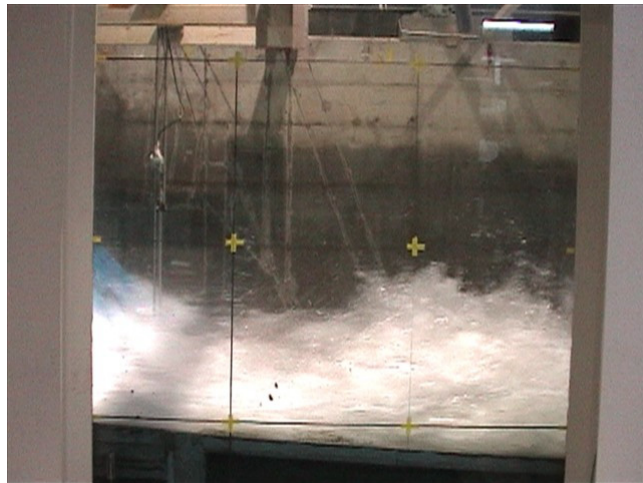


Photo 2 Wave Breaking off the Dike (T1m15)

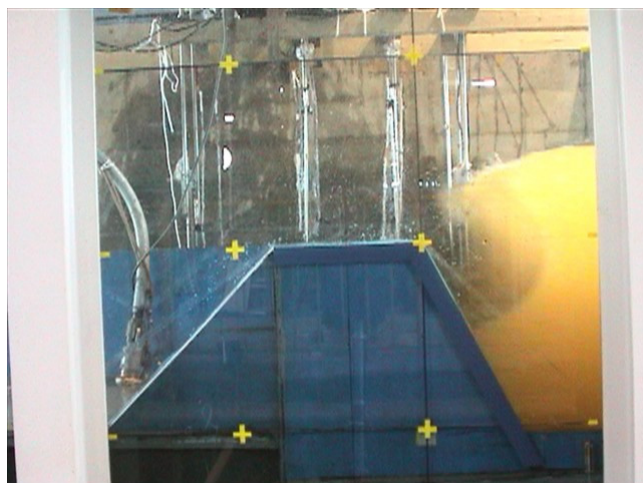


Photo 3 Collision of Breaking Wave to the Seaward Slope (T3p15)