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Development and verification of wall-flap-gate as tsunami inundation defence for nuclear plants

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ABSTRACT

A wall-flap-gate is automatic watertight door, and it works by buoyancy without powered machineries and human operations. In the Tohoku Earthquake tsunamis, serious damages were caused by inundation from ventilators of outer walls in power plants. The wall-flap-gate is estimated to be effective in keeping sustainability of nuclear plants against extreme tsunamis. The present study examines the hydrodynamic characteristics of the wall-flap-gate by hydraulic model experiments and verifies its capability of flood prevention for nuclear plants through various prototype tests.

The experimental results proved that the wall-flap-gate had sufficient strength, watertightness, and durability against tsunamis and that its motion was not disturbed by debris. The viability of the wall-flap-gate as an inundation defence structure for nuclear plants was confirmed through this study. As a result, practical wall-flap-gates are installing on Hamaoka nuclear power station in Shizuoka prefecture, Japan.

1. Introduction

A flap-gate type seawall, which usually lies down on ground surface, rises up by buoyancy due to tsunamis, surges, or flooding. It remains lying flat in usual conditions not to disturb traffic. In an emergence time, the flap-gate type seawall protects a target area from inundation without powered machineries and human operation. The seawall is called NEORISE (No Energy and no Operation RIsing Seawall, see Kimura et al., 2015).

In the Tohoku Earthquake tsunamis on March 11, 2011, serious damages were caused by inundation from ventilators of outer walls in power plants. For sustainability of nuclear plants against unexpected huge tsunamis, damages due to water leak from these ventilators must be prevented. Especially in Hamaoka nuclear power station, various measures in order to enhance functions and to guarantee a power supply in emergency including earthquakes and tsunamis are implemented (Yasuda et al., 2015). The present study develops an automatically closing gate attached to the outer wall (called wall-flap-gate, hereafter) by improving the previous NEORISE, and verifies its capability of preventing inundation for the nuclear power station.

This study carries out hydraulic model experiments and demonstration tests using a prototype wall-flap-gate. Data of tsunami forces for the structure design are collected through the model experiments. Strength and watertightness against water pressure, durability for repetitious motions, and influence of debris are examined through the prototype tests.

2. NEORISE

The NEORISE is expected to be implemental as part of a lock gate installation in gaps in inundation defence. Although a normal lock gate as a slide-type gate requires powered machinery and control system, the NEORISE requires neither since it is moved by buoyancy of the inundation water. The NEORISE consists of a gate serving as a float, side-walls and tension-rods, as shown in Fig. 1. A counterweight is equipped inside each side-wall and it is hung by a wire rope connected with pins, inserted grooves in the side-walls, through a pulley. These pins are set on both sides of the top. The counterweight assists the lying gate in rising up and it also brakes the moving gate before upright by turning

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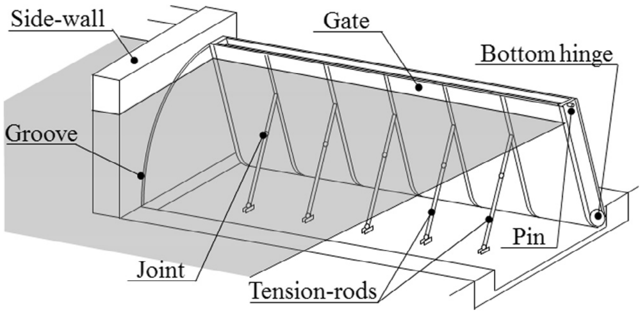

Fig. 1. Equipment for NEORISE.

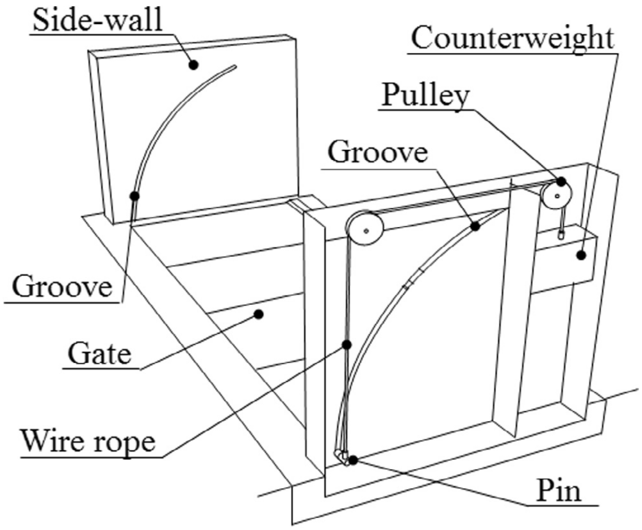

Fig. 2. Arrangement of counterweight.

direction of force by the counterweight according to an angle of the gate, as shown in Fig. 2.

The gate is formed from a hollow stainless steel box. The upper face of the NEORISE can be installed at the same level of the land surface; therefore, it does not prevent vehicles from passing over it. The hollow box is designed to support the weight of passing traffic whose wheel load is within 1 MPa. Hydraulic experiments have confirmed that the NEORISE can rise up correctly even when its upper surface matches the level of the surrounding ground. Fig. 3 shows a response of the NEORISE against tsunami flow running up the ground. These figures proved the reliability of the gate behavior against tsunamis (Kimura and Mase, 2014).

Water pressure acting on the upright gate is supported by both tension-rods and bottom hinges. The tension-rod has a joint between upper and lower connecting points, and it is folded below the gate when in its horizontal position. In order to prevent the leakage of water, rubber tubes are installed between the gate and side-walls and rubber sheet is covered on the bottom hinge. Each rubber materials are continuous at both sides of the bottom hinge.

3. Wall-flap-gate

The wall-flap-gate was developed to restrain water leak from ventilators on outer walls by improving the previous NEORISE.

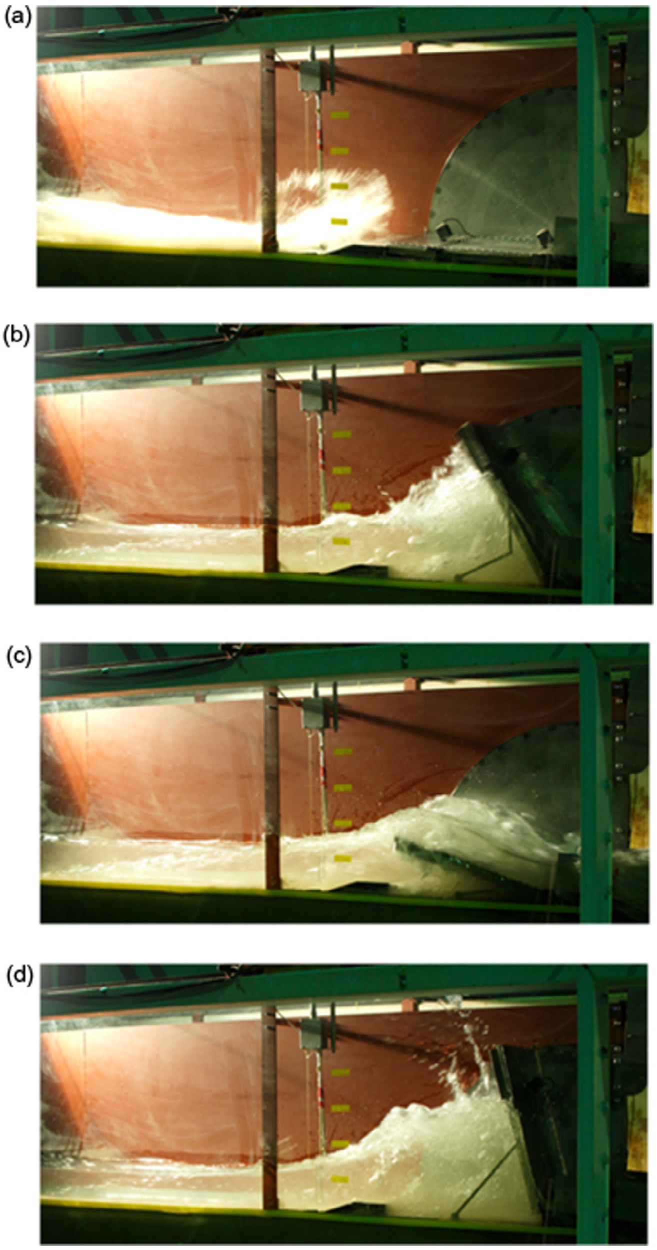

Fig. 3. Response of NEORISE against running up tsunami.

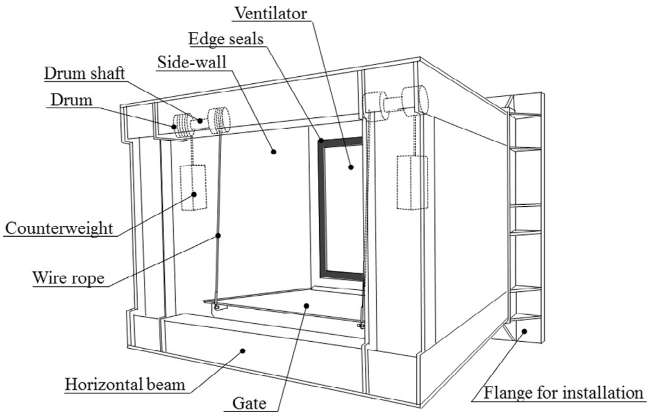

Fig. 4. Equipment for wall-flap-gate.

Fig. 4 shows the wall-flap-gate. Although the wall-flap-gate is equipped with a gate serving as a float and side-walls like the NEORISE, tension-rods are not present. The upright gate is supported by touching the edges of the ventilator and it restrains leakage with rubber seals along the edges. Both side-walls are connected by horizontal beams so as to withstand tsunami force and attacks of debris.

Although counterweights are equipped inside each side-wall as in the NEORISE, there is a small difference in the way of connection of wire ropes between the wall-flap-gate and the NEORISE. As mentioned above, the counterweights in the NEORISE are connected using pins inserted in the grooves of the side-walls. The wall-flap-gate's counterweight is hung through a drum which is set inside the side-wall, and another drum with the same shaft hung the top of the gate, as shown in Fig. 4. This system prevents foreign matter from entering the side-walls and makes it easy to access for maintenance.

Before becoming upright, rubber materials on the bottom and sides of the gate keep water sealing as in the NEORISE, and after becoming upright, as mentioned above, the edge seals of the ventilator restrain leakage.

The width of the wall-flap-gate is designed according to the horizontal size of the ventilator on the outer wall. Although the length of the gate is also determined by the vertical size of the ventilator, it is not advisable to have a very long gate from a point of view of earthquake resistance. Therefore the vertical size of the ventilator is complemented by piling up the wall-flap-gate which equips the gate under prescribed length as Fig. 5.

4. Hydrodynamic model experiment

This model experiment was carried out to obtain fundamental data for wall-flap-gate design and characteristics of wave pressure acting on the gate against bore-type tsunamis were evaluated (Kimura et al., 2012a,b). The experiment was conducted using a 1/16.5 scale model in a wave channel of size 50 m long, 1 m wide and 1.5 m high, located at the Disaster Prevention Research Institute, Kyoto University. Fig. 6 shows the experimental setup. A slope was installed on the wave channel to break a solitary wave generated by a piston-type wave maker, and a vertical partition-wall was installed in the channel to amplify the height of the breaking tsunami wave. The position of the wall-flap-gate model from the ground was 20 cm high and the height in real scale corresponded with 3.3 m high. Since the practical wall-flap-gate will be installed 10 m above the ground, experimental conditions were strict comparing with realistic conditions. The hydraulic model represented both an outer wall and the wall-flap-gate installed on the wall. In order to measure wave pressures acting on both of them, pressure gauges P1–P12 were set on surfaces of them, as shown in Fig. 7. In addition to pressure gauges, water-level meters H1–H3 and velocity meter V1 were set in the wave channel to evaluate wave conditions, and an angle sensor A1 was set on the wall-flap-gate to evaluate its response against tsunamis running up the ground. A propeller-type device was adopted as the velocity meter V1, and it was located at a height of 2 cm from the ground level. The data were recorded at a frequency of 1000 Hz. In the experiments, the heights of incidence tsunamis at H2 were varied between 3 and 10 cm by controlling the wave maker. These incidence tsunamis are dammed up by the experimental outer wall, and then inundation heights elevate rapidly and the gate closes at the same time. Each cases were labelled W1–W6 in increasing heights. Fig. 8 shows a time series of water level at H2.

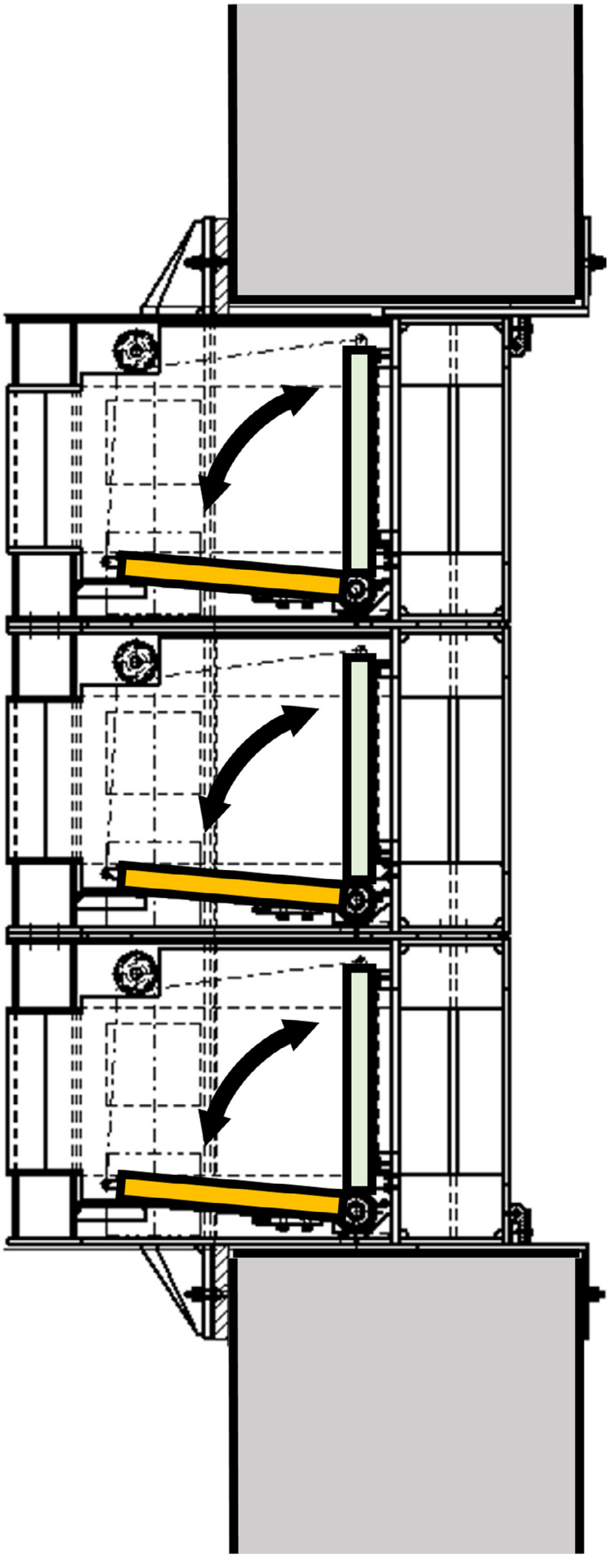

Fig. 5. Multi-stage type wall-flap-gate.

Fig. 9 shows an example time series of the water level of W6 and the gate angle, and Fig. 10 shows snapshots of water elevation and the gate response. The gate took 0.3 s to rise up from the lying position and it corresponded with about 1.2 s in real scale. As

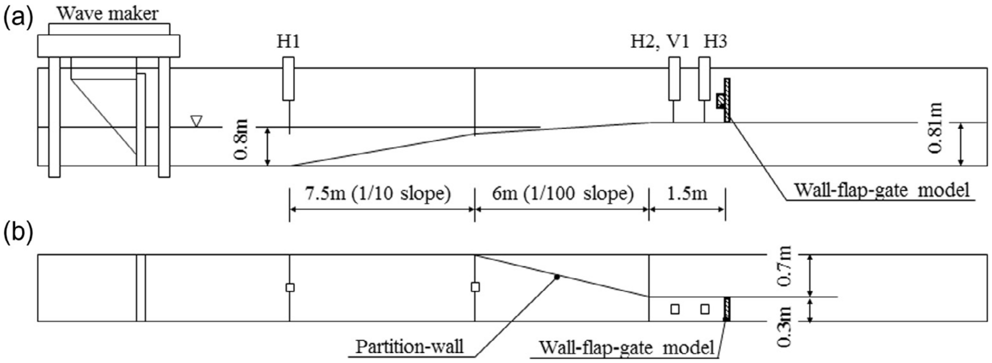

Fig. 6. Experimental setup. (a) Side view. (b) Plain view.

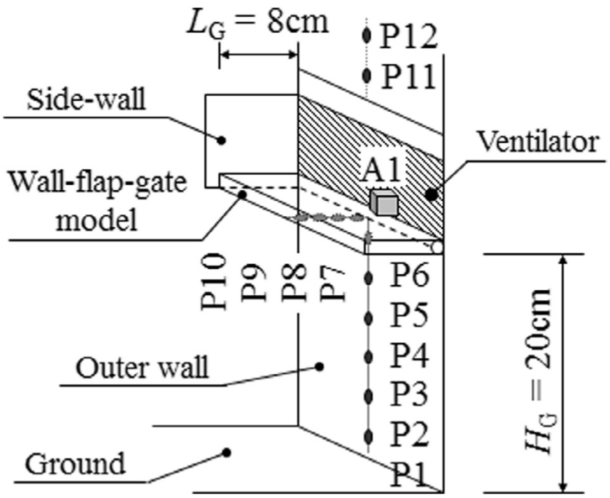

Fig. 7. Location of pressure sensors P1–P12.

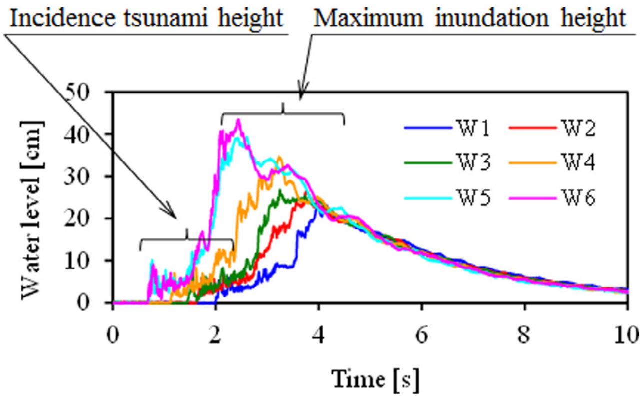

Fig. 8. Time series of water level of tsunami case W1–W6.

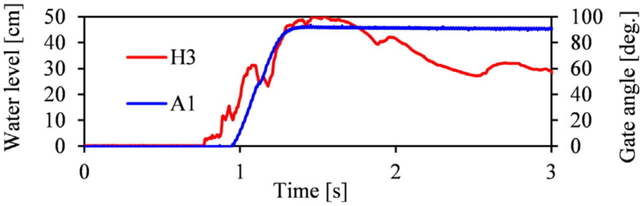

Fig. 9. Example of time series of water level by H3 and gate angle by A1.

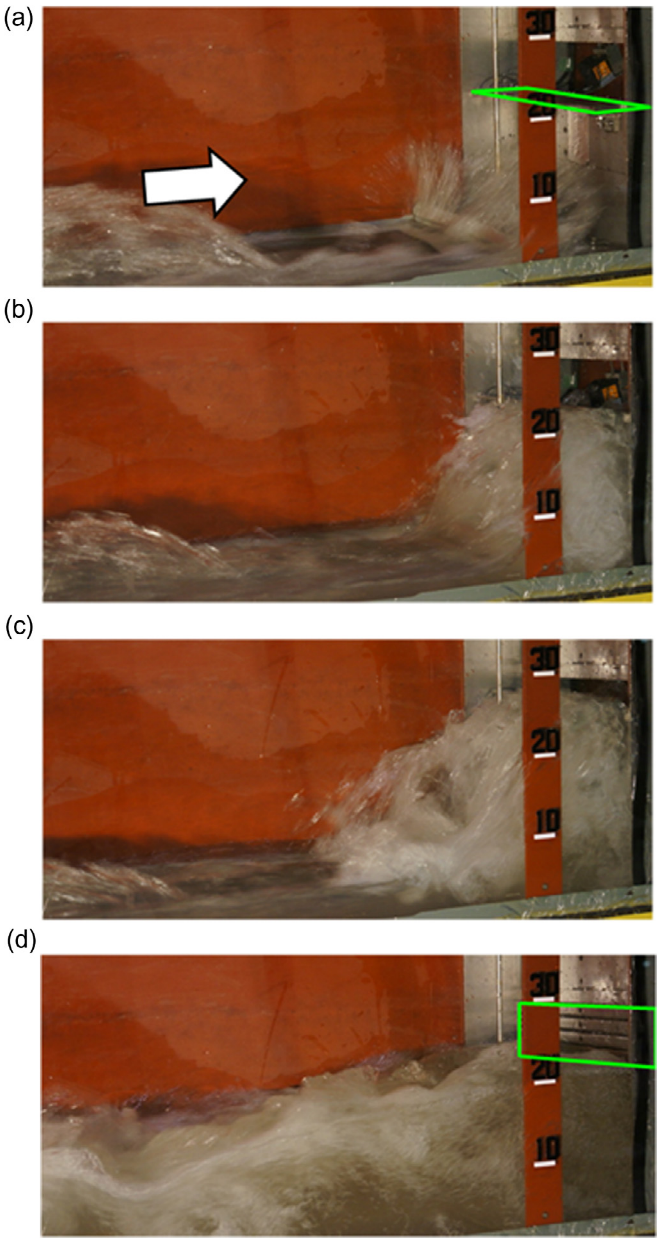

Fig. 10. Snapshots of water elevation and the gate response.

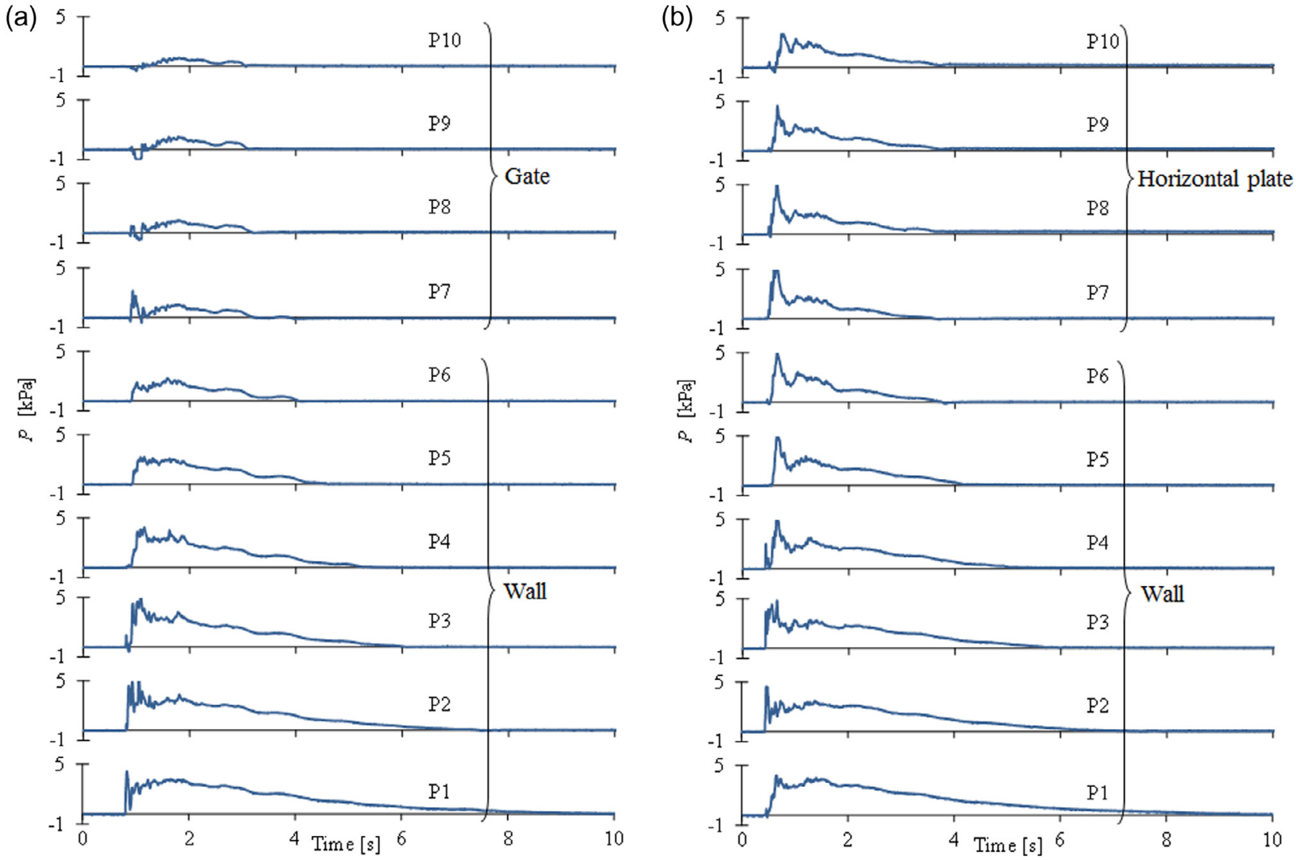

Fig. 11. Time series of wave pressure acting on movable gate and fixed horizontal plate. (a) Movable gate. (b) Fixed horizontal plate.

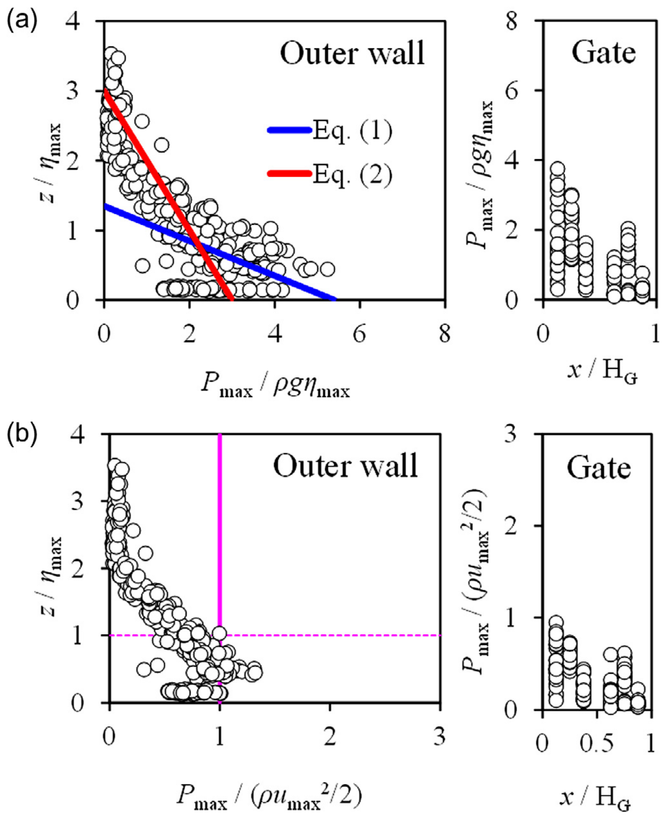

Fig. 12. Maximum pressure distribution. (a) Normalization by static pressure. (b) Normalization by dynamic pressure.

Table 1
Design conditions of demonstration wall-flap-gate model.

Size of ventilator	1100 mm (W), 1100 mm(H)
Hydraulic pressure	160 kPa
Wind load	3.6 kPa
Snow load	0.6 kPa

Table 2
Sizes and materials of demonstration wall-flap-gate model.

Size	Width	2420 mm
	Length	2080 mm
	Height	1940 mm
Weight		4786 kg
Material	Metal	Stainless steel (SUS329J4L)
	Rubber	Chloroprene

shown in these figures, the wall-flap-gate quickly responded against the tsunami flow. Against the other wave conditions, similar results were obtained, and the reliability of response was confirmed. Fig. 11 shows a time series of wave pressure acting on surfaces of the model equipped with a movable gate (a) or a fixed horizontal plate (b). This wave condition is the same as that of Fig. 9. As seen in these figures, the wave pressure acting on the fixed plate is larger than on the movable gate since the movable gate which represents the wall-flap-gate is displaced by the wave force acting on it. Wave pressure acting on the fixed plate was adopted as design conditions for the practical wall-flap-gate since

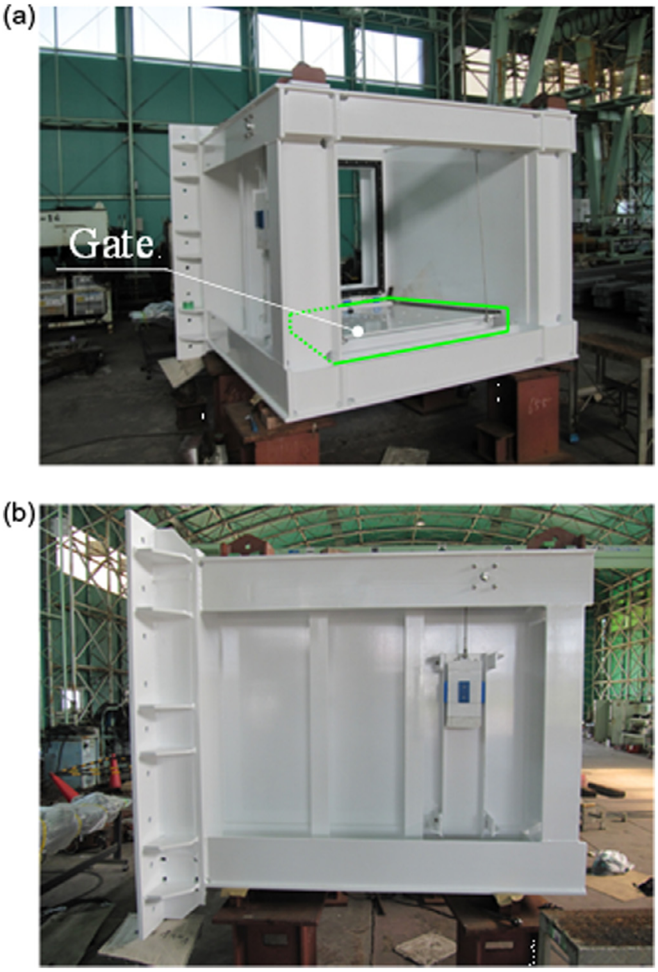

Fig. 13. Pictures of wall-flap-gate model. (a) Diagonal view. (b) Side view.

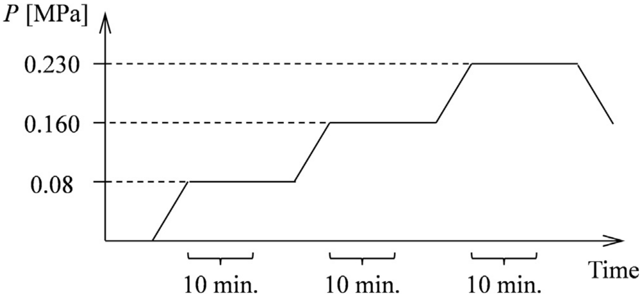

Fig. 15. Pressure curve.

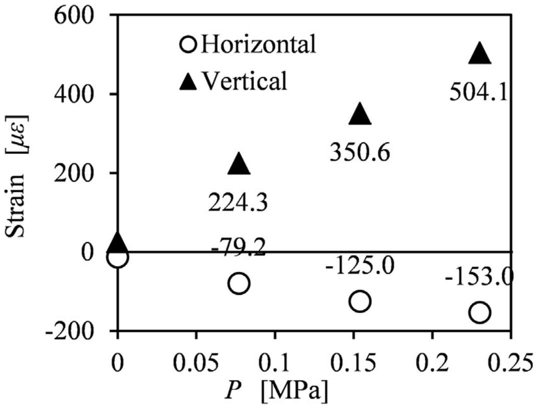

Fig. 16. Strain of beam under water pressure.

Table 3
Leakage water volume over 10 min from watertight rubber.

Pressure conditions	0 MPa	0.08 MPa	0.16 MPa	0.23 MPa
Leakage water volume	0.4 l	0 l	0 l	0 l

it was proved that wave pressure acting on the movable gate does not exceed that of the fixed plate. Fig. 12 shows the maximum pressure distribution, which is normalized by static pressure due to maximum tsunami height $\eta_{\max}$ or dynamic pressure due to horizontal maximum tsunami velocity $u_{\max}$, acting on the vertical wall and the movable gate. Here, ρ is the density of water, g is the acceleration due to gravity, x is the horizontal distance from the wall, z is the vertical distance from the ground and L_G is the gate length. As shown in Fig. 12, it was confirmed that wave pressure normalized by the static pressure corresponded with previous study (Asakura et al., 2002) as an Eq. (1), which is brought mainly

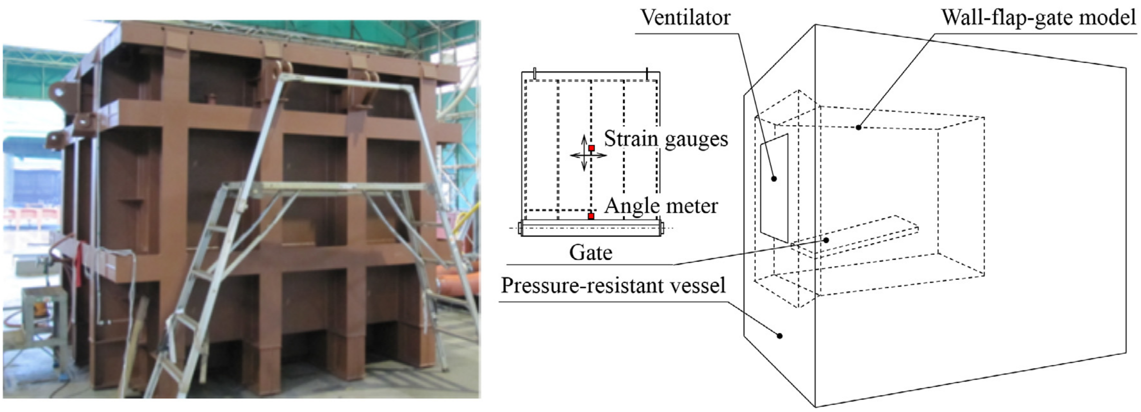

Fig. 14. Experimental setup.

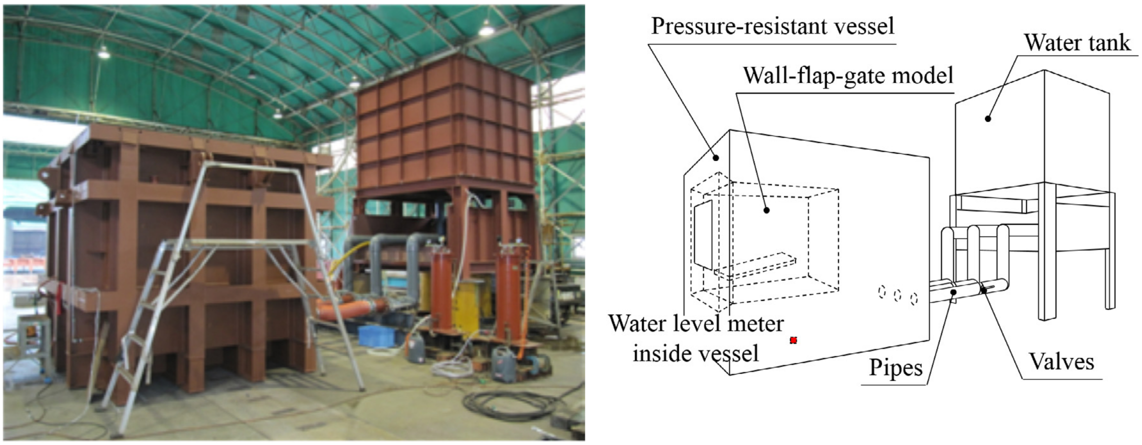

Fig. 17. Experimental setup.

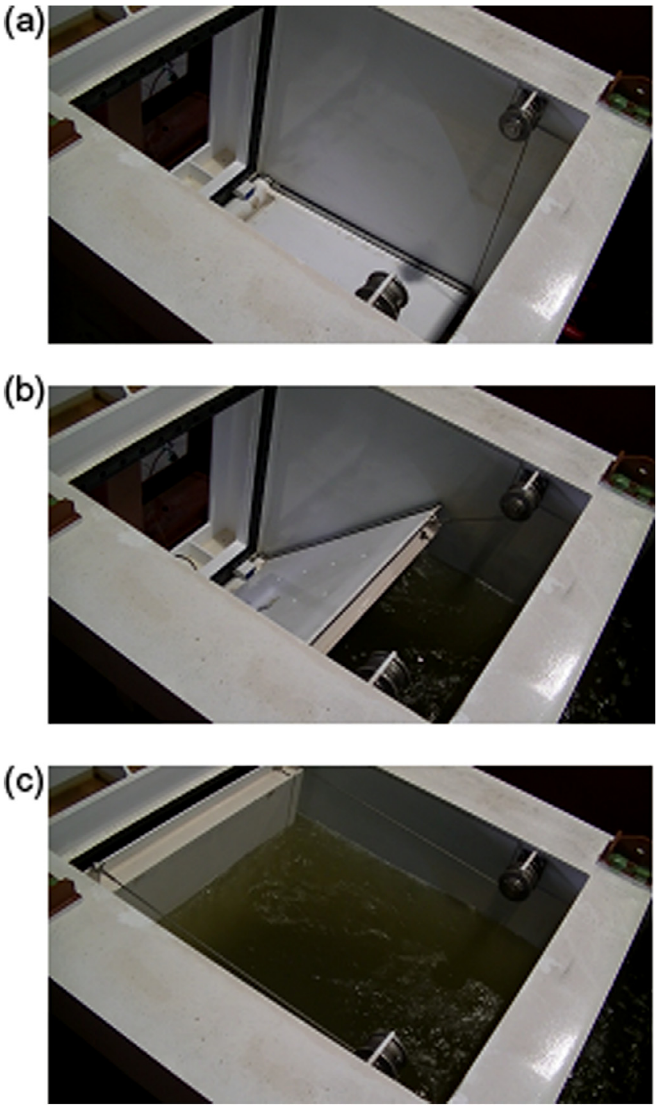

Fig. 18. Snapshots of gate motion. (a) Lying. (b) Rising. (c) Standing.

by dynamic water pressure, and an Eq. (2), which is brought mainly static water pressure in maximum water level. Remarkably, wave pressure normalized by the velocity did not exceed $P_{\max}/(\rho u_{\max}^2) = 1.0$.

$$\frac{p_{max}(z)}{\rho g \eta_{max}} = 5.4\left(1 - \frac{z}{1.35\eta_{max}}\right) \qquad (1)$$

$$\frac{p_{max}(z)}{\rho g \eta_{max}} = 3\left(1 - \frac{z}{3\eta_{max}}\right) \qquad (2)$$

Maximum wave pressure acting on the gate was reduced near the top of the gate and wave pressure near the base of the gate was almost the same with $P_{\max}/(\rho u_{\max}^2) = 1.0$. Since the top of the gate leave a stream of water rapidly, wave pressure on it is mitigated. The moment acting on the gate due to wave force became much lighter by restraining wave pressure from acting near the top of the gate.

5. Hydrodynamic demonstration tests

A demonstration model was designed and manufactured according to the conditions shown in Table 1 and these design conditions were the same as the practical equipment. Table 2 shows the scales and materials of the model, and Fig. 13 shows pictures of the model. In this chapter, pressure and motion tests using demonstration model of the wall-flap-gate are described.

5.1. Strength and leakage against water pressure

In this pressurization test, the wall-flap-gate model was inserted inside a pressure-resistant vessel then was pressured by a compressor and an accumulator, and strains on a beam and leakage water from the watertight rubber were measured. Fig. 14 shows experimental setup. Strain gauges were set on the center of the vertical beam, and the strength of the point on which gauges set was relatively inferior among members composing the gate. Maximum pressure under this test corresponded to 1.5 times the design conditions and it was pressured along a pressure curve as shown in Fig. 15.

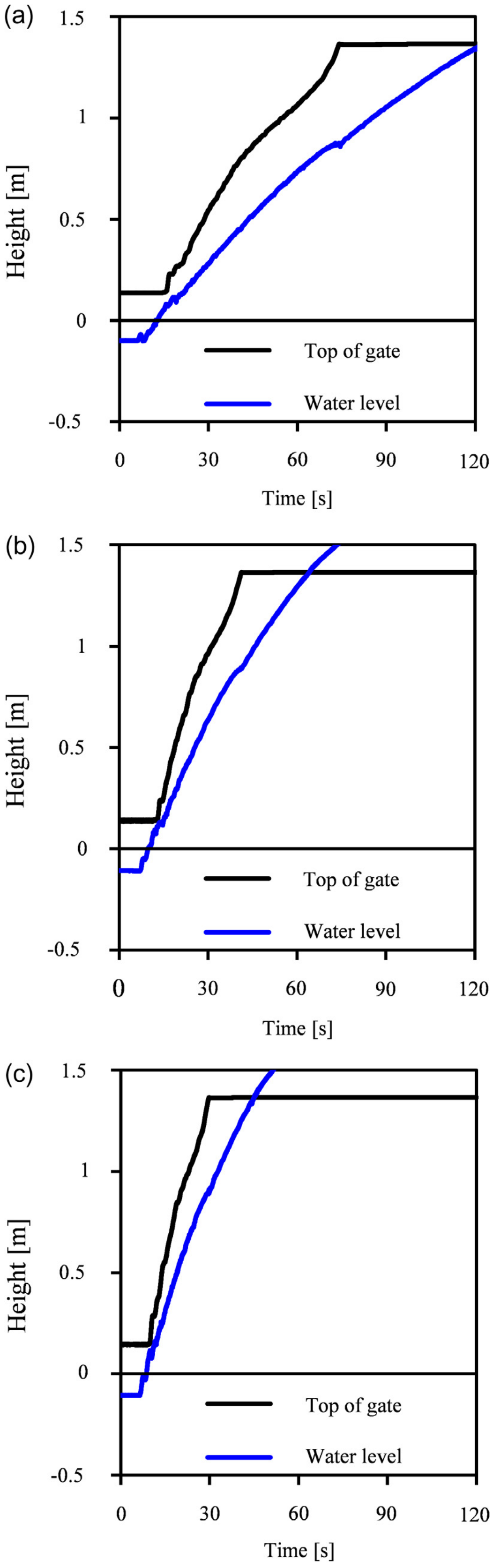

Fig. 19. Time series of top level of gate and water level. (a) Elevation: 0.9 m/min. (b) Elevation: 1.7 m/min. (c) Elevation: 2.6 m/min.

Fig. 16 shows strains of the beam when water pressure acted on the model. As shown in this figure, the vertical direction of the beam expanded according water pressure, while the horizontal direction of the beam contracted about 30% of the vertical increase. Poisson's ratio of a material composing the model is about 0.3 and then, relations between vertical and horizontal strains corresponded with the Poisson's ratio. Relations between external forces due to water pressure and strains were linear, and these variations were within an elastic region. Through this pressurization test, it was proved that the strain under pressure beyond the design condition was below proof stress and that the model representing the practical equipment has strength enough to withstand water pressure beyond estimated maximum tsunamis.

Leakage water volume from the watertight rubber under pressurization tests is shown in Table 3. These data indicate water volume over 10 min. The more pressure acted on the model, the more leakage water decreased as shown in this table since the watertight rubber touched strongly due to water pressure. This leakage was small enough to protect plants against an inundation.

5.2. Repetitious motion against elevation

In these repetitious motion tests, water stored in a tank was poured into the vessel which contained the wall-flap-gate model as shown in Fig. 17. These tests were carried out over 100 times under various pouring conditions. The pouring speed was controlled by handling valves between the tank and the vessel. Maximum inundation speed in the vessel was about 2.6 m/min when all valves were opened completely.

Fig. 18 shows snapshots of gate motions and Fig. 19 shows time series of gate heights and water levels under 3 inundation speeds. Each level in Fig. 19 indicates heights from a rotational center of the gate. In a case where the gate was higher than the water level, overtopping did not occur beyond the top of the gate. As shown in Fig. 19, the top levels of the gate were high compared with the water levels, and the same results were obtained through 100 tests. Although the two curves in each of these figures cross after the gate has reached maximum height, water flow is blocked since the gate is closed at that time. Maximum leakage water from watertight rubber was 670 cm^3 over 100 gate motions and is sufficiently small to maintain functions of the plants.

5.3. Response against tsunami wave

In this response test, solitary and periodic waves acted on the wall-flap-gate model installed in a wave channel of size 200 m long, 4 m wide and 6 m high, located at the Central Research Institute of Electric Power Industry, Japan. Fig. 20 shows an experimental setup and a vessel was installed behind the model in order to measure overtopping quantities. Fig. 21 shows an example of the solitary wave profile at H1–H6 adopted in this experiment. The solitary wave generated by the wave maker was broken on a slope of the wave channel and it attacked the model as a bore-type tsunami.

Fig. 22 shows an example of time series of gate response and water level at H6 according to the solitary wave. As in Fig. 19, no overtopping occurred when the top of the gate was higher than the water level. As shown in Fig. 22, the water level was temporar-

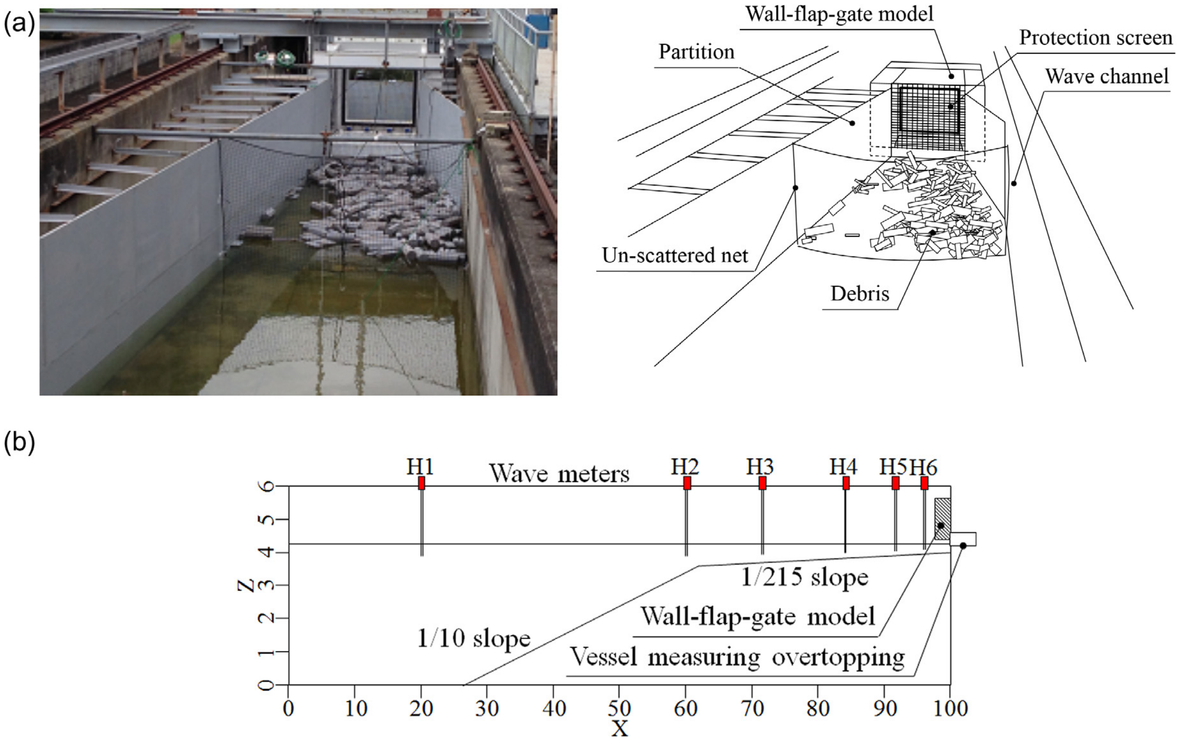

Fig. 20. Experimental setup. (a) Air view. (b) Side view of wave channel.

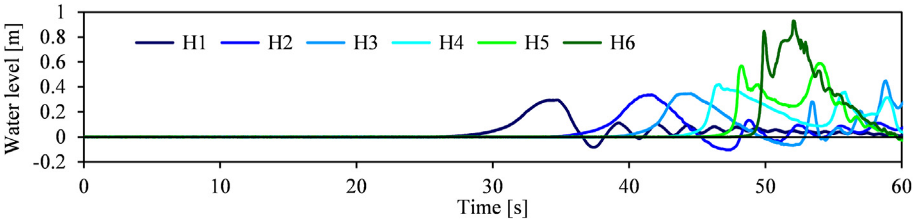

Fig. 21. Example of time series of solitary wave profile.

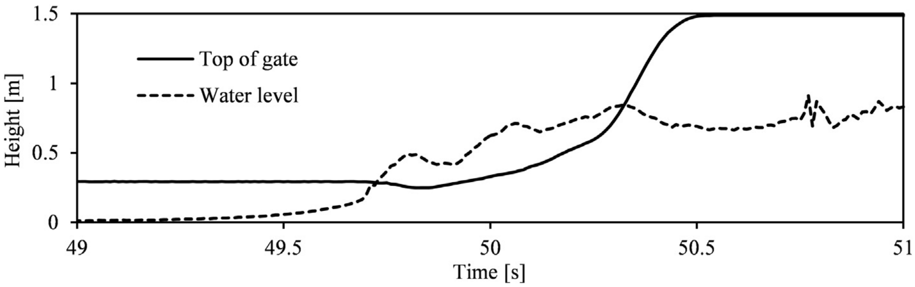

Fig. 22. Time series of gate response and water level.

ily higher than the gate. Although the maximum overtopping quantity reached about 0.4 m^3 in this experimental case, it was within a range as no facilities, which were arranged behind the practical wall-flap-gate, damage.

The influence of debris or sediment was also evaluated in this experiment. Fig. 23 shows snapshots of drifting debris according to a bore-type tsunami, and a plastic screen for protection against drifting debris is set in front of the wall-flap-gate. It was confirmed that the screen caught debris and that gates motions were not disturbed by debris. Sediment also did not prevent gate motion.

6. Conclusions

Through hydraulic model experiments and various tests with practical equipment, performance of the wall-flap-gate against tsunamis was evaluated. As a result, it was proved that this structure has sufficient strength and efficiency for water sealing to protect nuclear plants against inundations due to tsunamis. In Hamaoka nuclear power station, practical wall-flap-gates are installing on outer walls of a reactor building as an inundation defence system against unexpected huge tsunamis

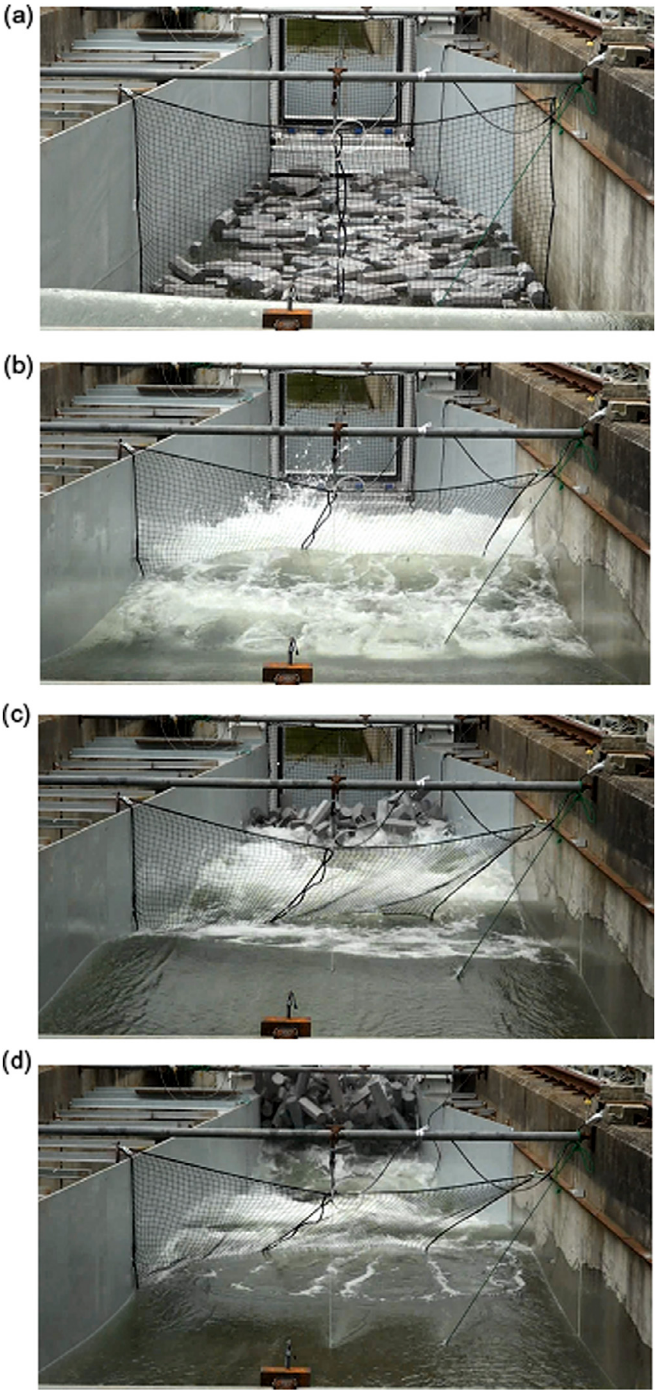

Fig. 23. Snapshots of drifting debris and protection screen.

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