

DEVELOPMENT AND VERIFICATION OF WALL-FLAP-GATE AS AN INUNDATION DEFENCE FOR NUCLEAR PLANTS

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INTRODUCTION

A flap-gate seawall which usually lies down on ground rises up by buoyancy during inundation due to tsunamis and storm surges. It keeps lying in usual time to secure traffic and landscape. In emergence time, the flap-gate seawall protects a target area from inundation without power machineries and human operation. The seawall is called as NEORISE (No Energy and no Operation RIsing SEawall).

In the Tohoku Earthquake tsunamis on March 11, 2011, serious damages were caused by inundation from ventilators on outer walls in power plants. For sustainability of nuclear plants against unexpected huge tsunamis, damages due to leaks from these ventilators have to be prevented. The present study develops a wall-attached type flap-gate (called as wall-flap-gate, hereafter) by improving the previous NEORISE, and verifies hydrodynamic characteristics of the wall-flap-gate and capability of preventing inundation for plants.

This study carries out hydraulic model experiments and demonstration tests using a prototype of practical wall-flap-gate. Data concerning tsunami forces for the structure design are collected through the model experiments. Strength and water-tightness against water pressure, durability for repetitious behaviours and influences of debris are verified through the prototype tests.

NEORISE

The NEORISE is expected to apply as parts 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 systems, the NEORISE requires neither since it is moved by buoyancy of 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, inserting ditches of side-walls, through a pulley. These pins are set on both sides of the top of the gate. The counterweight assists the lying gate in rising up and it also brakes the moving gate before standing, 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. Hydraulic experiments have confirmed that the NEORISE can rise up correctly even when its upper surface matches the level of the surrounding ground. Figure 3 shows a response of the NEORISE against tsunami flow running up the ground. These figures proved the reliability of the gate behaviour against tsunamis (Kimura et al., 2014).

Water pressure acting on the upright gate is supported by both tension-rods and bottom hinges. Tension-rods are folded below the gate when in its horizontal position. Rubber sheets and tubes prevent the leakage of water from a bottom line and side lines of the gate.

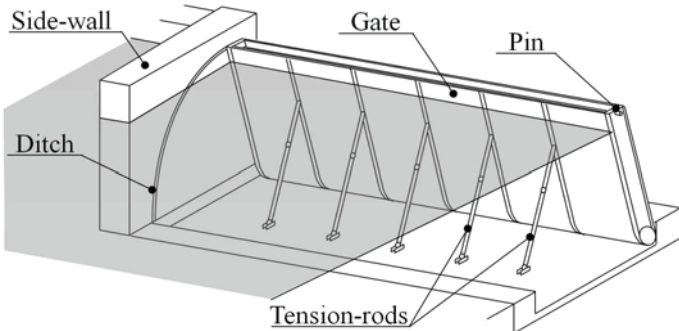


Figure 1. Equipment for NEORISE.

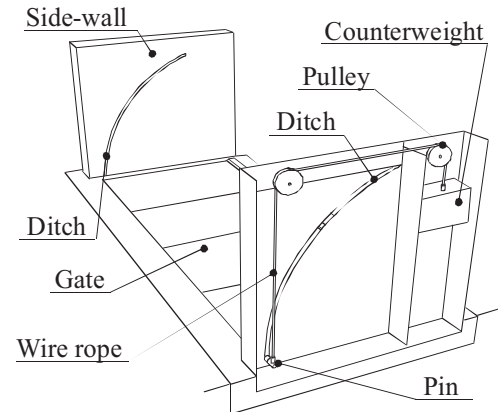
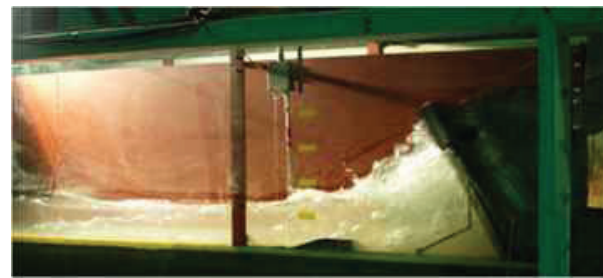


Figure 2. Device of counterweight.



(a)



(b)



(c)



(d)

Figure 3. Response of NEORISE against running up tsunami.

WALL-FLAP-GATE

The wall-flap-gate was developed to restrain leaks from ventilators on outer walls by improving the previous NEORISE. Figure 4 shows the wall-flap-gate. Although the wall-flap-gate equips a gate serving as a float and side-walls like the NEORISE, tension-rods are not equipped. The upright gate is supported by touching edges of the ventilator and it restrains leakage with rubbers on the edges. Both side-walls are connected by horizontal beams so as to withstand tsunami force and attack of debris.

Although counterweights are equipped inside each side-wall as the NEORISE, there is a small difference in the way of connection of wire ropes between the wall-flap-gate and the NEORISE. Counterweights of the NEORISE are connected using pins inserting ditches of side-walls. Wall-flap-gate's weight 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 matters from coming into side-walls and makes it easy to access for maintenance.

Before upright, both rubber seals on the bottom and side of the gate keep water sealing as the NEORISE, and after upright, as above-mentioned, touch on edge seals of the ventilator restrains leakage.

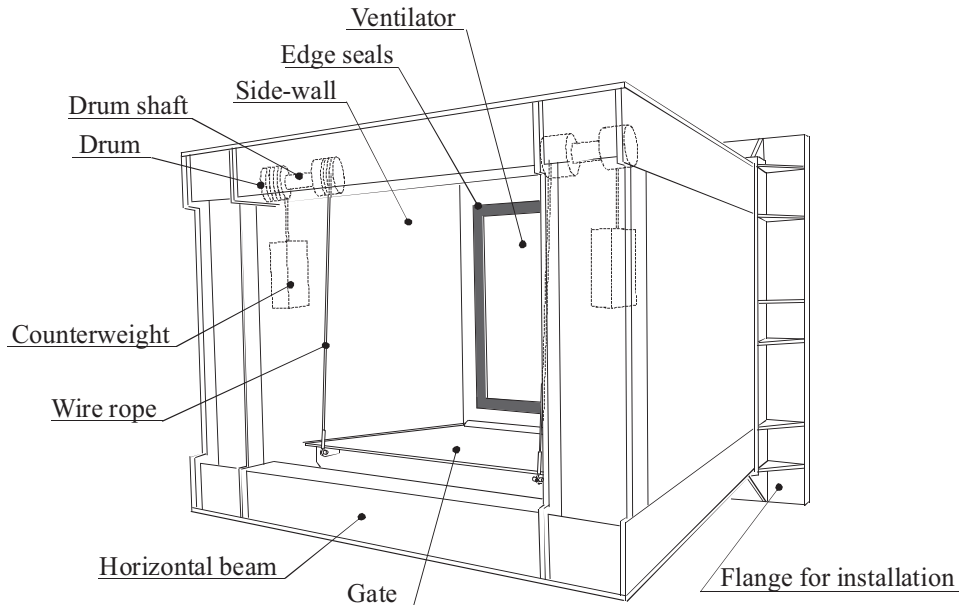


Figure 4. Equipment for wall-flap-gate.

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., 2012). The experiment was conducted by a 1/16.5 scale model in a wave channel, with 50 m long, 1 m wide and 1.5 m high, located at Disaster Prevention Research Institute, Kyoto University. Figure 5 shows experimental setup. A slope was installed on the wave channel to break a solitary wave generated by a piston-type wave maker, and a partition was installed in the channel to amplify a height of breaking tsunami wave. A 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 practical wall-flap-gate will be installed above 10 m high from the ground, experimental conditions were strict comparing with realistic conditions. The hydraulic model represented both an outer wall and 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. 6. Except pressure gauges, wave gauges 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. 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 tsunamis were labelled as W1 – W6 with increasing their heights. Figure 7 shows time series of water level at H2.

Figure 8 shows an example of time series of both water level by W6 and gate angle, and Fig. 9 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 shown these figures, the wall-flap-gate quickly responded against flow of tsunami. Against the other wave conditions, the similar results were obtained, and the reliability of response was confirmed. Figure 10 shows time series of wave pressure acting on surfaces of the model which equips a movable gate (a) or a fixed horizontal plate (b). This wave condition is the same as that of Fig. 8. As these figures, wave pressure acting on the fixed plate is larger than the

movable type, since the movable gate which represents the wall-flap-gate is transferred by wave force acting on itself. Figure 11 shows maximum pressure distribution, which is normalized by static pressure due to maximum tsunami height η_{\max} or dynamic pressure due to horizontal maximum tsunami velocity u_{\max} , acting on the vertical wall and the movable gate. Here, ρ is density of water, g is acceleration of gravity, x is horizontal distance from the wall, z is vertical distance from the ground and L_G is the gate length. As shown in Fig. 11, it was confirmed that wave pressure normalized by the static pressure was corresponded with previous study (Asakura et al., 2002) as following equations (1) – (2). Wave pressure normalized by the velocity did not exceed $P_{\max}/(\rho u_{\max}^2) = 1.0$ remarkably.

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

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

Maximum wave pressure acting on the gate reduced near the top of the gate and it was almost the same with $P_{\max}/(\rho u_{\max}^2) = 1.0$. These data were utilized for design of the practical wall-flap-gate.

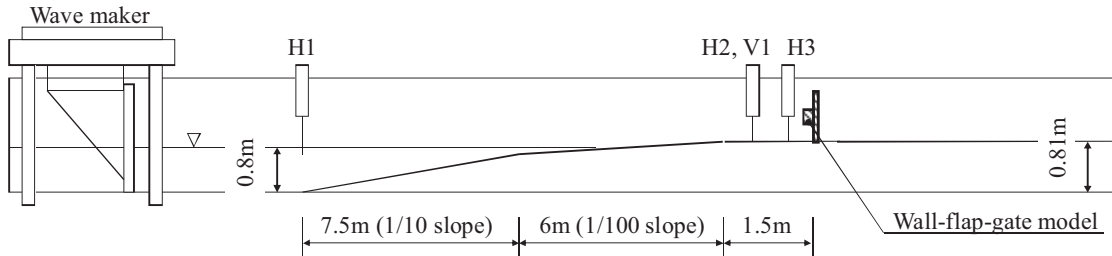


Figure 5. Experimental setup.

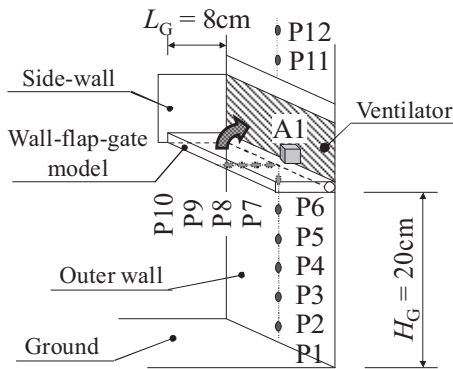


Figure 6. Location of pressure sensors P1 – P12.

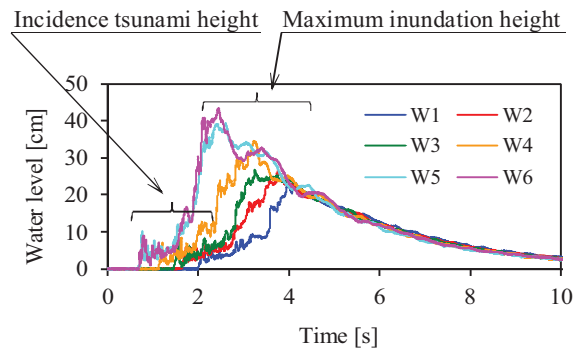


Figure 7. Time series of water level of tsunami case W1 – W6.

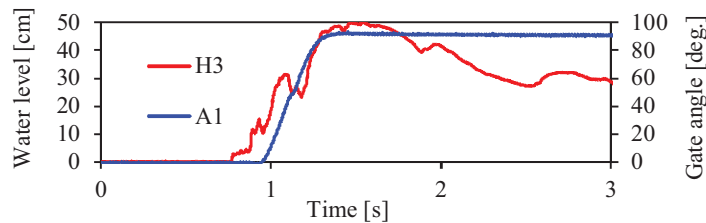


Figure 8. Example of time series of water level by H3 and gate angle by A1.

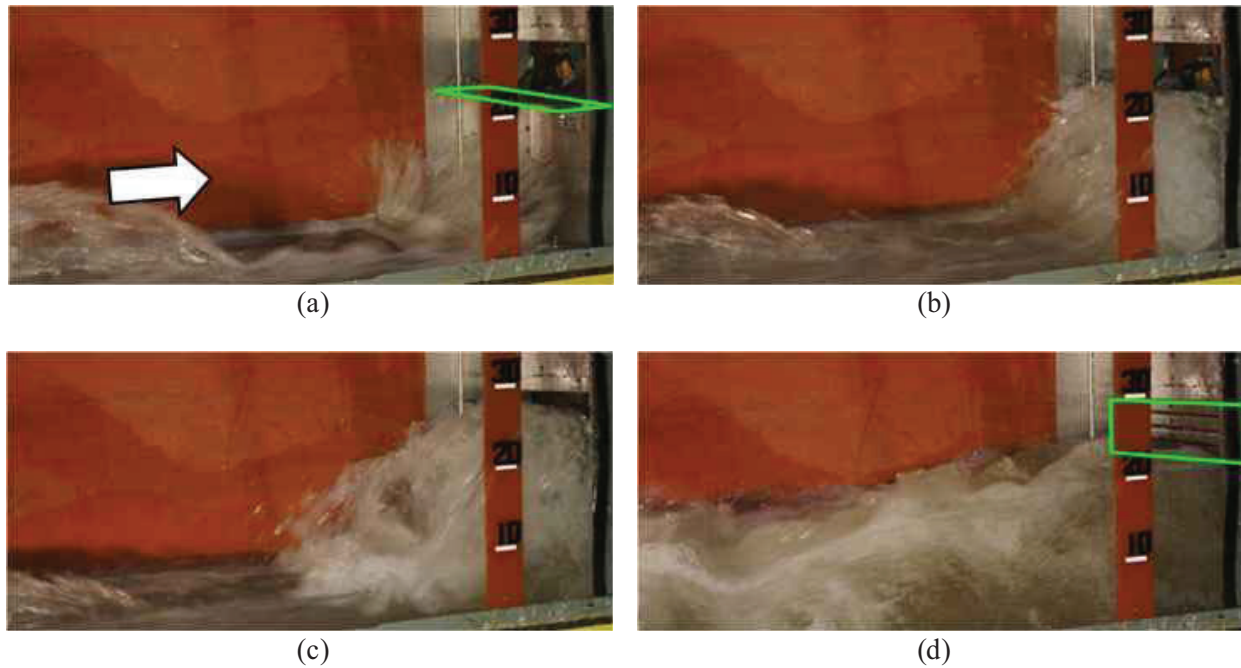


Figure 9. Snapshots of water elevation and the gate response.

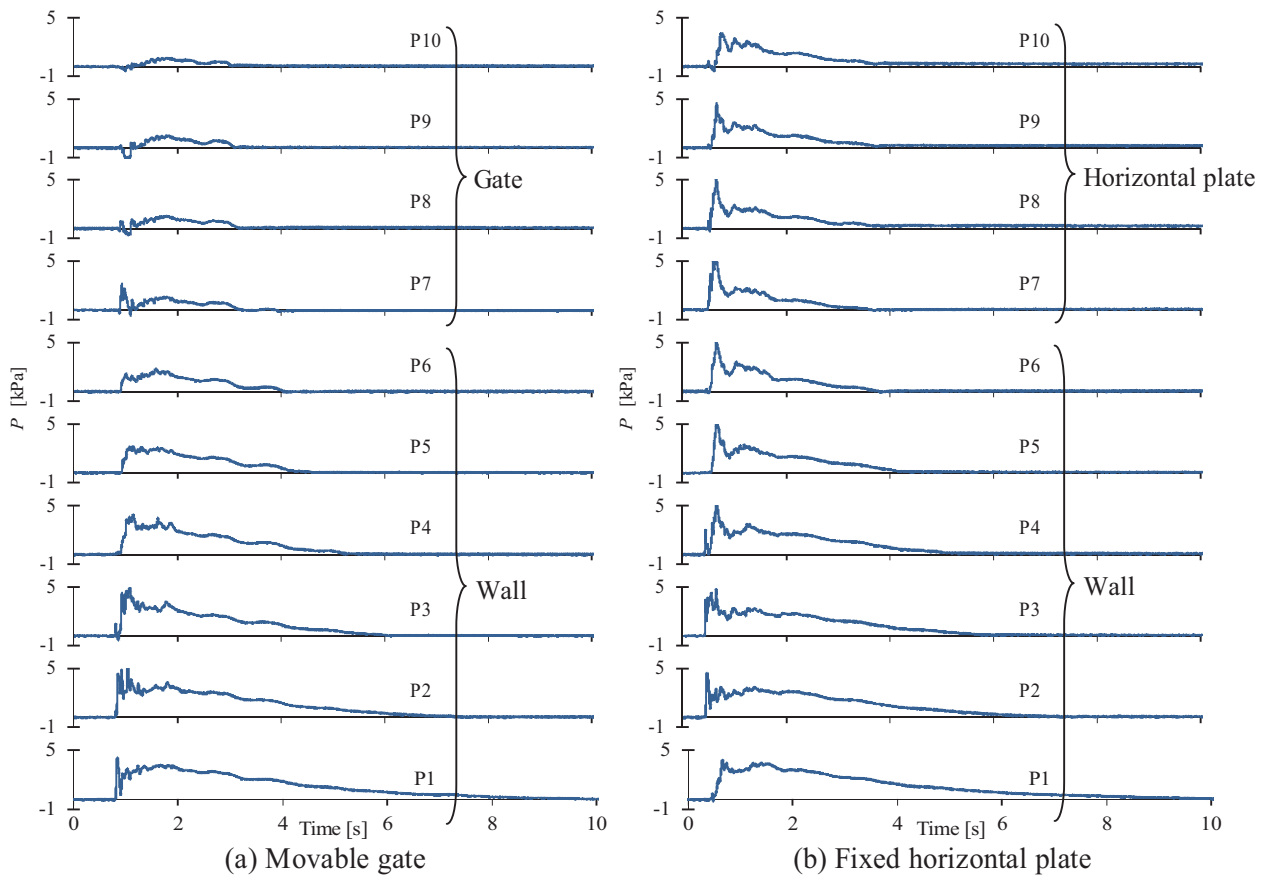


Figure 10. Time series of wave pressure acting on movable gate and fixed horizontal plate.

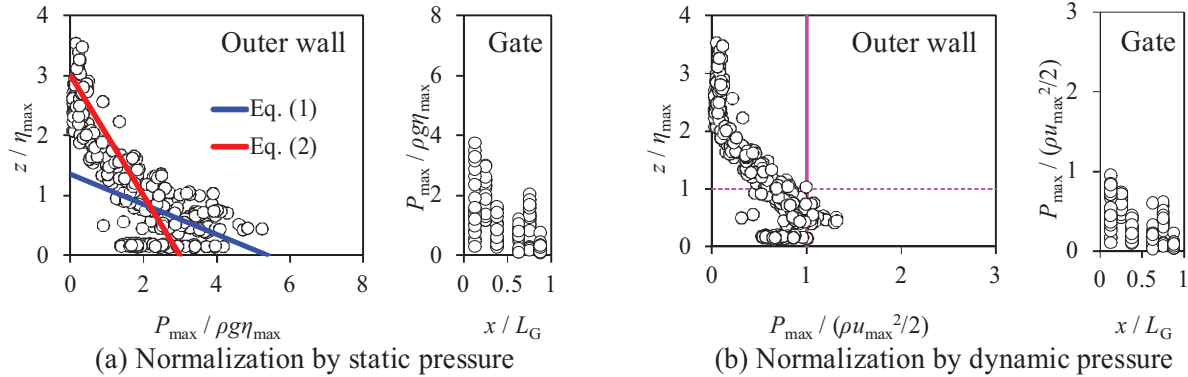


Figure 11. Maximum pressure distribution.

HYDRODYNAMIC DEMONSTRATION TESTS

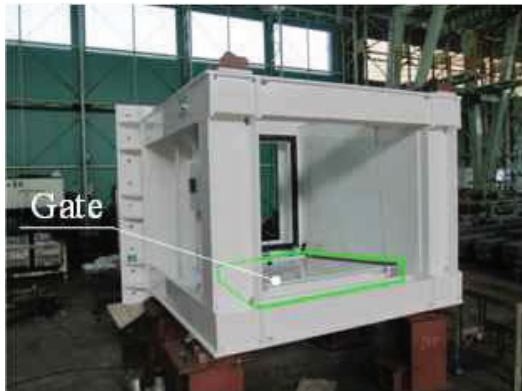
A demonstration model was designed and manufactured along conditions shown by Table.1 and these design conditions were the same as the practical equipment. Table 2 shows scales and materials of the model, and then Fig. 12 shows pictures of the model. In this chapter, pressure and motions tests using demonstration model of wall-flap-gate are described.

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

	Design conditions
Size of ventilator	1100mm (W), 1100mm(H)
Hydraulic pressure	160 kPa
Acceleration by earthquake	Horizontal: 2.6G, Vertical: 1.0G
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



(a) Diagonal view



(b) Side view

Figure 12. Pictures of wall-flap-gate model.

Strength and leakage against water pressure

In this pressurization test, the wall-flap-gate model inserted inside pressure-resistant vessel was pressured by a compressor and an accumulator, and strains on the beam of gate and leakage water from the watertight rubber were measured. Figure 13 shows experimental setup. Maximum pressure under this test was corresponded to 1.5 times of design conditions and it was pressured along a pressure curve as shown in Fig. 14. Strain gauges were set on a point where strength was inferior relatively.

Figure 15 shows strains of the beam when water pressure acted on the model. As shown in this figure, a vertical direction of the beam expanded according water pressure, while a horizontal direction of the beam contracted about 30 % of the vertical increase. Poisson's ratio of material composing the model is about 0.3 and then, the vertical strain brought the horizontal strain. Through this pressurization test, it was proved that the strain under pressure beyond the design condition was below proof stress and that the model represented the practical equipment has strength enough to withstand water pressure due to estimated maximum tsunamis.

Leakage water volume from the watertight rubber under pressurization tests is shown as Table 3. These data indicate water volume by 10 minutes. 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 less enough to protect plants against an inundation.

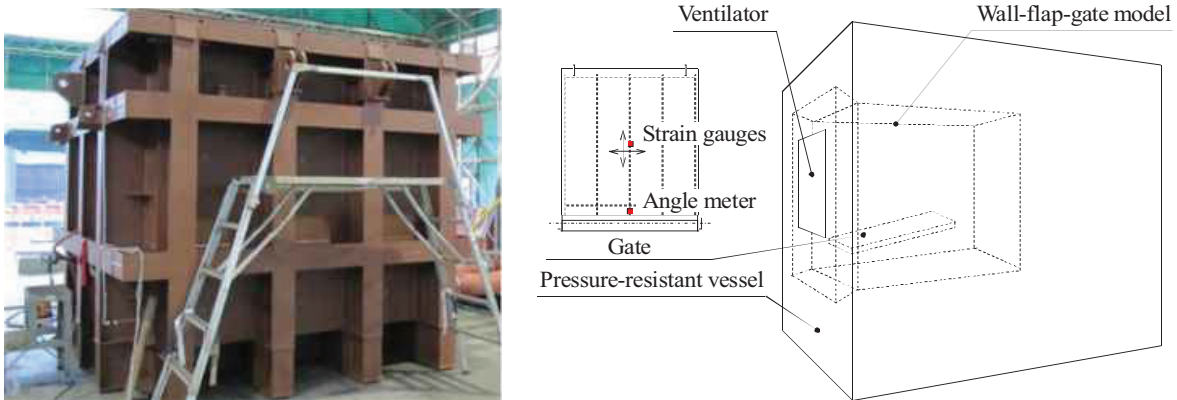


Figure 13. Experimental setup.

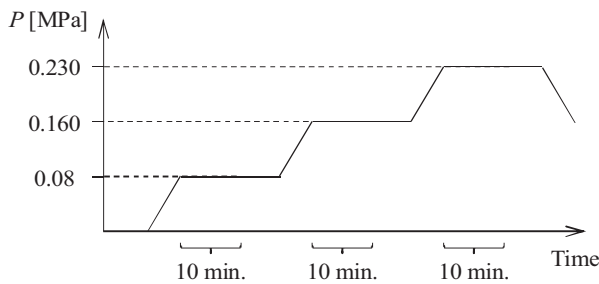


Figure 14. Pressure curve.

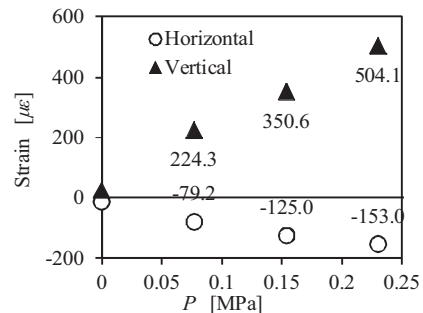


Figure 15. Strain of beam under water pressure.

Table 3: Leakage water volume by 10 minutes 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

Repetitious motion against elevation

In these repetitious motion tests, water stored in a tank was poured into the vessel which inserts the wall-flap-gate model as shown in Fig. 16. These tests were carried out beyond 100 times under various pouring conditions. A pouring speed was controlled by handling valves between the tank and the vessel. A maximum inundation speed in the vessel was about 2.6 m/min when all valves opened perfectly.

Figure 17 shows snapshots of gate motions and Fig. 18 shows time series of gate heights and water levels under 3 inundation speeds. Each level in Fig. 18 indicates heights from a rotational centre of the gate. If the gate was higher than a water level in this figure, an overtopping did not occur beyond the top of the gate. As shown in Fig. 18, the top levels of the gate were high comparing with the water levels and the same results were obtained through 100 times tests. Maximum leakage water from watertight rubber was 670 cm³ through gate motions of 100 times and it was also less enough to maintain functions of plants.

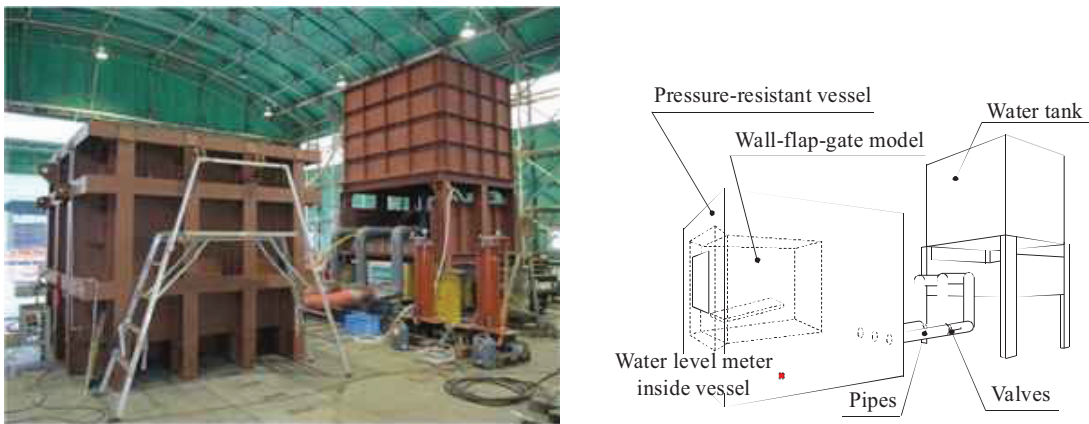


Figure 16. Experimental setup.



Figure 17. Snapshots of gate motion.

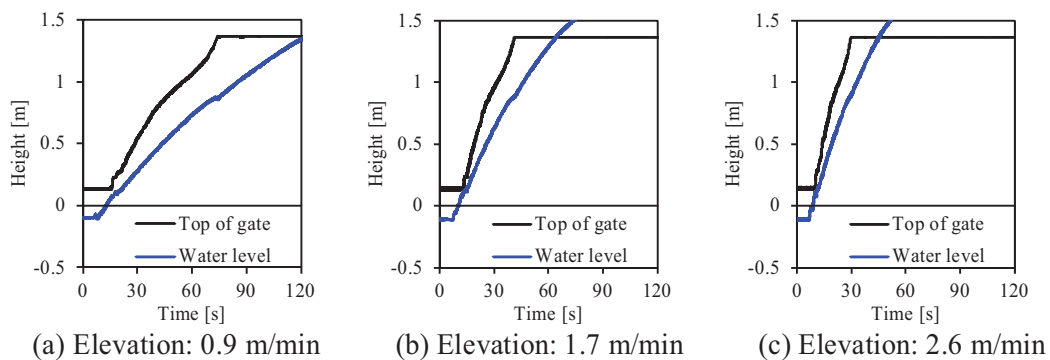


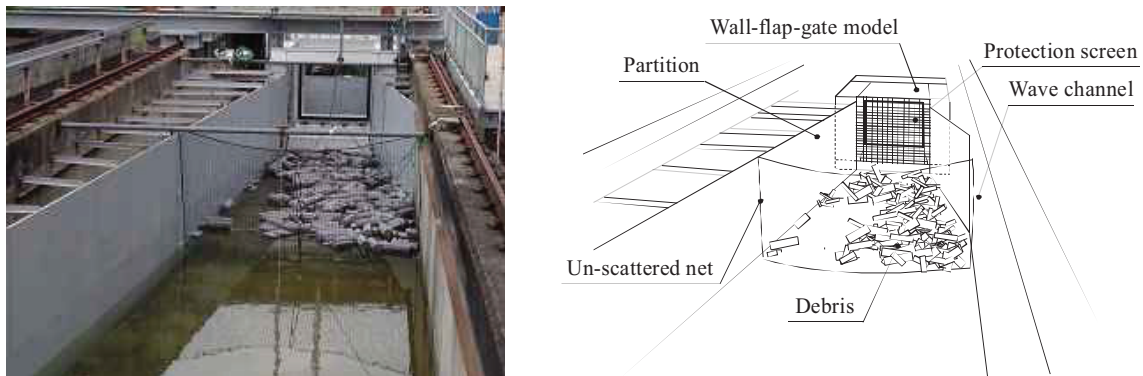
Figure 18. Time series of top level of gate and water level.

Response against tsunami wave

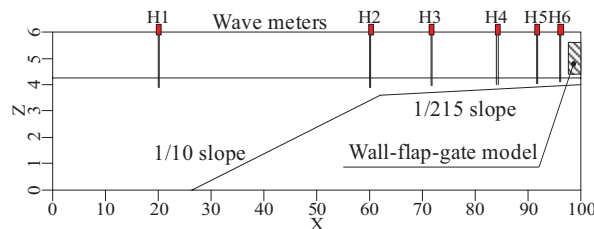
In this response test, solitary and periodic waves were acted on the wall-flap-gate model installed in a wave channel with 200 m long, 4 m wide and 6 m high, located at Central Research Institute of Electric Power Industry, Japan. Figure 19 shows an experimental setup and Fig. 20 shows an example of solitary wave profile adopted in this experiment. A solitary wave generated by wave maker was broken on a slope of the wave channel and it attacked the model as a bore-type tsunami.

Figure 21 shows an example of time series of gate response and water level at H1– H6 according to the solitary wave. As the same with Fig. 18, an overtopping did not occur, when the top of the gate was higher than a water level. As shown in Fig. 21, water level was high in comparison with the gate temporarily. Although maximum overtopping quantity reached about 0.4 m³ in this experimental case, it was much below the level as facilities installed behind the wall-flap-gate damage.

In addition, influence of debris or sediment was also evaluated in this experiment. Figure 22 shows snapshots of drifting debris according to a bore-type tsunami. As shown in Fig. 22, a plastic screen for protection against drifting debris was set in front of the wall-flap-gate. It was confirmed that the screen caught debris and that gates motions were not disturbed. Sediment did not also prevent gate motion.



(a) air view



(b) Side view of wave channel
 Figure 19. Experimental setup.

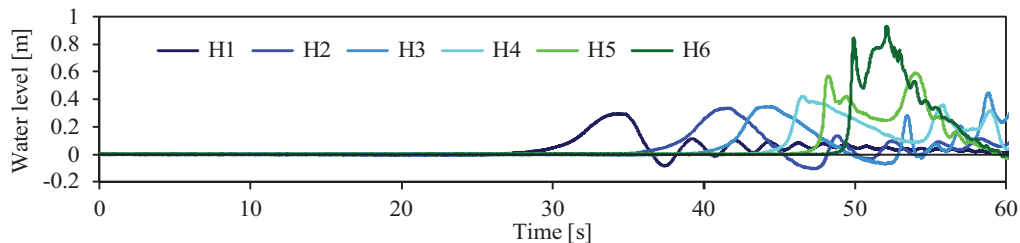


Figure 20. Example of time series of solitary wave profile.

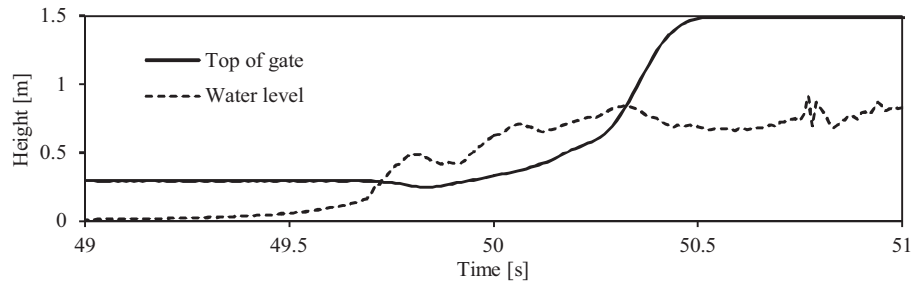


Figure 21. Time series of gate response and water level.

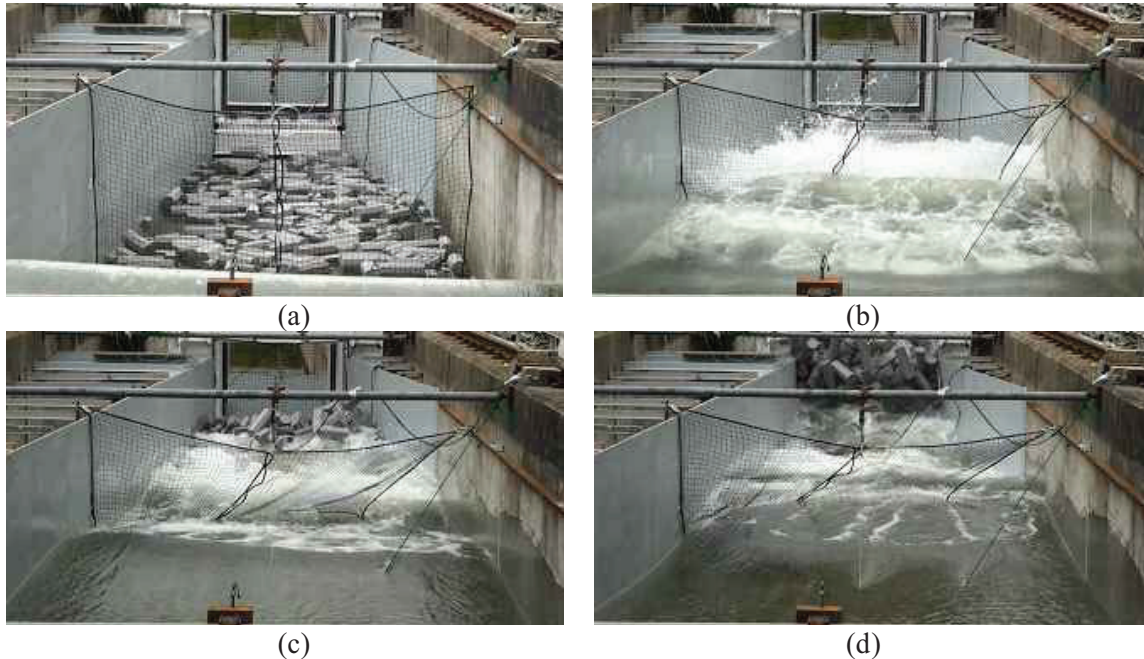


Figure 22. Snapshots of drifting debris and protection screen.

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 strength and efficiency for water sealing enough to protect nuclear plants against inundations due to tsunamis.

REFERENCES

- Asakura, R., Iwase, K., Ikeya, T., Takao, M., Kaneto, T., Fuji, N. and Ohmori, M. (2002). "The Tsunami Wave Force Acting on Land Structure", Proc. of 28th Int. Conf. on Coastal Engineering, ASCE, pp.1191-1202.
- Kimura, Y., Yamakawa, Y., Kawabata, T., Mizutani, N., Hiraishi, T. and Mase, H. (2012). "Experimental Study for Response of Wall Attached-type Flap-gate against Bore-type Tsunamis", *Journal of JSCE, Ser. B2 (Coastal Eng.)*, Vol.68(2), pp.246-251 (in Japanese).
- Kimura, Y. and Mase, H. (2014). "Numerical Simulation of a Rising Seawall for Coastal Flood Protection", *Journal of Waterway, Port, Coastal, and Ocean Eng., ASCE*, Vol.140(3), 04014002.