FLAP GATE TO PREVENT URBAN AREA FROM TSUNAMI

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ABSTRACT :

Authors propose the flap gate to protect against tsunamis and have begun studies on the hydraulic characteristics and on the design of the gate. When danger of a tsunami is predicted, the flap stands up in a couple of minutes to protect coast inhabitant area from Tsunami invasion. In this paper, we discuss two-dimensional hydraulic model tests in a flume tank using a bore wave generator to confirm the wave pressure and gate behavior required for flap gate design. In addition, hydraulic characteristics due to tsunami were simulated using the VOF method to compare the results of the model tests. The results of numerical analysis generally tracked the results obtained in the model tests. However the wave pressure in numerical analysis did not agree with the results of the model tests in wave breaking condition. Three dimensional FEM by Flow 3D also simulated run-up behavior of Tsunami at a port area where the flap gate was installed at a mouth of the port. Through the test and calculation, flap gate for Tsunami is efficient for Tsunami invasion to port inhabitant area.

KEYWORDS: Tsunami, Flap gate, Model test, Numerical simulation, Tsunami wave force

1. NTRODUCTION

Japan has many Tsunami attack history along the coast line to lose many lives and properties. Recent forecasts also predict damages due to the large-scale earthquakes that will be accompanied by tsunami. Therefore improvements to tsunami countermeasures in coastal areas are demanded. Authors propose the use of flap gate as one of these countermeasures and are currently conducting studies on hydraulic properties. As shown in Fig. 2, a flap gate is designed with a pin mechanism at the bottom edge and is normally positioned on the seabed. When a tsunami is forecasted to hit the coastal area, the cells in the flap is inflated with air so that it will have the buoyancy to float rapidly upwards. After tsunami has passed by, the water is filled in the cells in the gate to sink again on the seabed. The duration of flap operation is set at several minutes for tsunamis. Although an operating mechanism for flap gate has already been adopted in the “Progetto Moze” in Italy, that gate is suitable as a storm surge but as not tsunamis. The flap gate introduced here is installed at the mouth of a bay or river to prevent coast inhabitant area from tsunami. This gate can be also installed on land along the coastline to prevent cities from invasion of Tsunami run-up. The installation of flap gates is in the planning stage for several areas in Japan. To confirm the validity of the flap gate, hydraulic model test and numerical simulation were carried out.

Figure 1 Tsunami attacks coast line

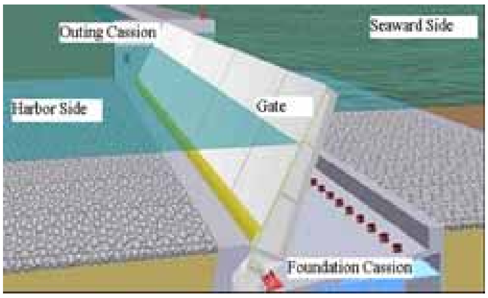

Figure2 Outline of a flap gate

2. OUTLINE OF MODEL TESTS

2.1 FLAP GATE MODEL

There are two kinds of floatable flap gates: one type controls flap movement using stoppers installed on the lower surface of the flap, while the other stabilizes the flap with a truss mechanism by rods and cables. The flaps move freely in the seaward direction but cannot move towards land. In addition to flaps that are perpendicular or inclined to seaward when closed.

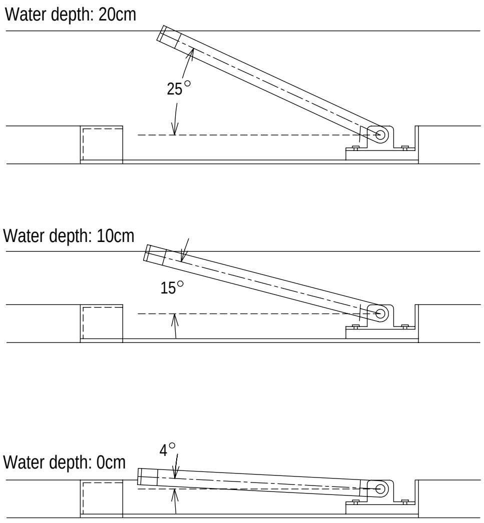

Figure 3 Initial stage of the gate

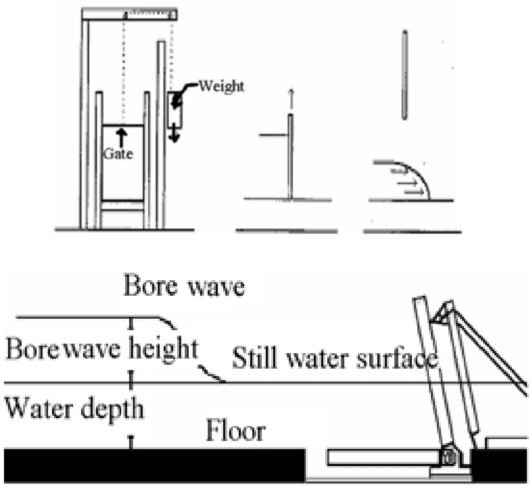

Figure 4 Generation of Tsunami (bore wave)

The scale of the models was set at S=1/50. The angle of the flaps was set at 75° and 90°. The tension rod is set so that it is straight and inclined at an angle of 39° from horizontal. The tension rod is manufactured using three stainless steel beams with a rectangular section and is pin-connected. In its initial position, the tension rod is installed in a tri-fold state on the seabed. Fig. 3 shows the initial installed position of the model. With the arrival of a tsunami bore wave, the flap floats upward due to buoyancy and lift. Even if a bore wave arrives when the water level is zero, the flap can easily moves to instantly upwards as the water level rises. This means that the flap gate is applicable for land area such as on the road or the revetment along the coast line. The flap was manufactured using acrylic and polyvinyl chloride plates that are filled with styrene foam. The mass of the structure is 19.4 kg, and the model structure measures 475 mm in height, 790 mm in depth and 50 mm in thickness.

The tests were conducted in a flow tank with the gate-lift bore generator shown in Fig. 4. The experimental flume dimension is 25,000 mm in length, 1,000 mm in width (water flow section), and 1,500 mm in height. The water storage tank is located on the left side of the waterway, and the bore waves are generated by quickly lifting the front door (bore generation gate) by means of a heavy weight. This method is also called the dam breaking method. The flap model is designed so that it can be installed on the flume's channel floor and it is 735 mm in length and 100 mm in depth.

2.2 MEASUREMENT METHOD

Flap behavior and the tsunami wave form were recorded using a digital video camera. The water level and flow velocity of the bore waves were measured by installing six capacitive-type wave height meters. The flow velocity was calculated by measuring the time difference between meters at a specified water level and then dividing the distance between the meters by that time difference. In the fixed model tests, the wave pressure was measured by arranging nine wave pressure gauges at 5 cm intervals. In the oscillating model tests, the wave pressure was measured by installing wave pressure gauges at five positions. In the fixed model tests, the load cell was attached to a position 450 mm from the flap's center of rotation and perpendicular to the flap in order to measure the rotation moment working on the flap. In the oscillating model tests, a strain gauge was attached on the rod at a position 450 mm from the flap's center of rotation to measure the rod tension force; the rotation moment was calculated using the horizontal component of the force.

2.3 Test result

Photo 1 shows a bore wave at the flap gate. Bore waves were generated by the wave generator using different initial water levels that varied in 10-cm intervals from 10 cm to 70 cm. Fig. 5 shows the time-history water level of the bore waves as measured at wave height meter, which was located in front of the flap. The reference wave height for wave velocity was, in each case, properly set by choosing a section with stable wave height. In regard to water level measurement, the point at 100 data units (0.1 sec.) prior to where the water level reached 0.2 cm above the initial water level at wave height meter was set as zero for the time-history change, and measurements were taken until the reflected wave returned to the gate of the bore wave generator.

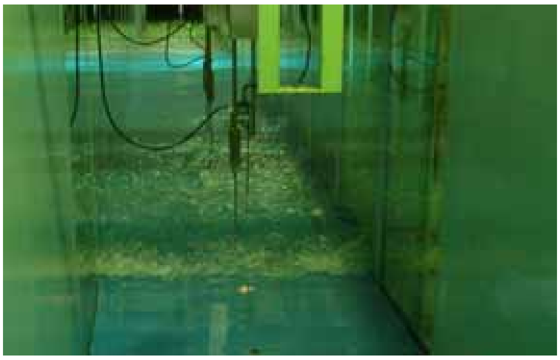

Photo 1 Propagation of bore wave in flume

Photo 2 Breaking of a bore wave

Notable differences were confirmed with regard gate, depending on the angle of the flap and the gate support system and assuming that overtopping did not occur. An example of the deformation of a tsunami (h=10 cm and ⊿h=30 cm) for a fixed model is shown in Photos 2. When the bore wave arrived at the flap, a breaking wave was occurred. Wave moved vertically upwards when the flap angle was 90° and was discharged upward and seaward along the angle of the flap when set at 75°. After the breaking wave occurred, the water level rose and overtopped the gate. When the bore wave height and water depth were low, overtopping did not occur. When overtopping did happen as shown in photo3, there was no notable difference in flaw behavior regardless of the flap angle or the support system. With the oscillating model, upon arrival of a bore wave, the flap instantly began to revolve upwards on its lower axis of rotation. As the bore wave rose upward, it was not seen to overtop the flap and flow to the shoreward side, thereby confirming the efficiency of the flap for the tsunami.

Photo 3 Overtopping at the gate(fixed type90°)

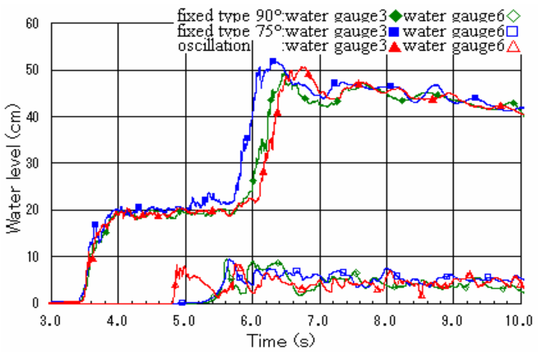

Figure 5 Time history of water level

According to past research, there are two peaks in wave pressure over time when a bore wave applies on an upright wall: an abrupt peak in wave pressure that is generated when the bore wave arrives at the flap and a sustained peak of wave pressure that is caused by the rising water level in front of the flap. In the current study, the former is classified as impulsive wave pressure and the latter as sustained wave pressure. As an example of the time-history of wave pressure, Fig. 6 shows the measured results using the fixed model (75°) when h=20 cm and ⊿h=50 cm. Impulsive wave pressure arose at about the 4th second, when the bore wave arrived at the flap gate; subsequently, sustained wave pressure was generated for about 4 seconds and was gradually decreased. The water level reached its maximum when the impulsive wave pressure arose and then remained nearly constant.

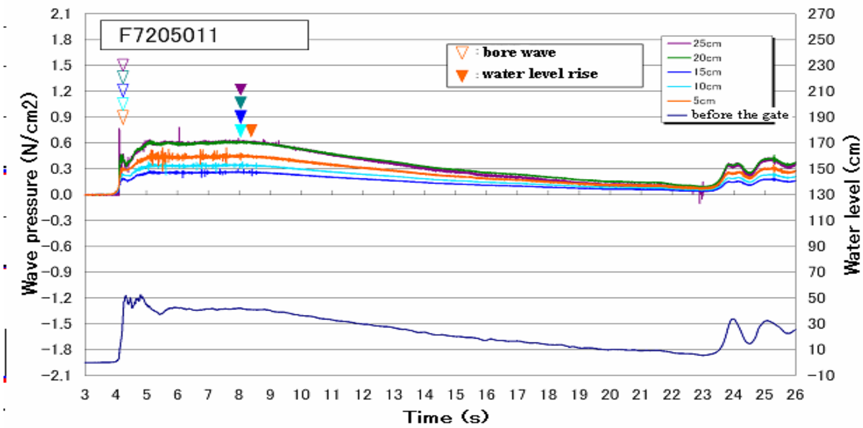

Figure 6 Wave pressure time history

2.5 VERTICAL DISTRIBUTION OF IMPULSIVE WAVE PRESSURE

With regard to the vertical distribution of the bore wave as it breaks up, Ikeno et al.[6)] have proposed the following equation.

$$P/(\rho \cdot g \cdot a_H) = 2.2(1 - z/3a_H) \cdot \alpha \qquad \text{When } (0 \le z/a_H \le 3) \tag{2.1}$$

$$P/(\rho \cdot g \cdot a_H) = 2.2\alpha \qquad (z/a_H \le 0) \tag{2.2}$$

Where, *P*: maximum wave pressure, *z*: upward positive coordinate for still sea level
a_H: progressive bore wave amplitude, *p*: density of liquid, *g*: gravity acceleration
α: coefficient of wave pressure due to breaking wave, and the following values are given

$$\alpha = 1.36 \quad (0 \le z/a_H \le 3), \tag{2.3}$$

$$\alpha = 1.36(1 + 0.52z/a_H) \quad (-0.5 \le z/a_H \le 0) \tag{2.4}$$

$$\alpha = 1.0 \quad (z/a_H \le -0.5) \tag{2.5}$$

As an example of the test results, Fig. 7 shows the measured results for impulsive wave pressure taken at various points when h=10 cm and ⊿h=50 cm and the results obtained using the equations proposed by Ikeno and Tanimoto. In the measurement results by use of the equation proposed by Tanimoto with the condition of no wave breaking, the vertical distribution of impulsive wave pressure shows the linear distribution from 0 at the height of 3ζ on the still water level to 2.2 W_0H on the calmed water surface, and the distribution below the water surface shows the uniform distribution. The ordinate axis indicates the distance made dimensionless using the bore wave. Fig-8 shows vertical distribution of height, and the abscissa indicates the wave pressure impulsive wave pressure strength made dimensionless using the bore wave height and the unit mass weight. The impulsive wave pressure obtained in all test cases showed values larger than the wave pressure distribution proposed by Ikeno, et al. and Tanimoto, et al. A comparison by flap angle shows that the impulsive wave pressure at 75°was larger than that at 90°, and with regard to the type of support used, the oscillating model registered greater impulsive wave pressure than did the fixed model.

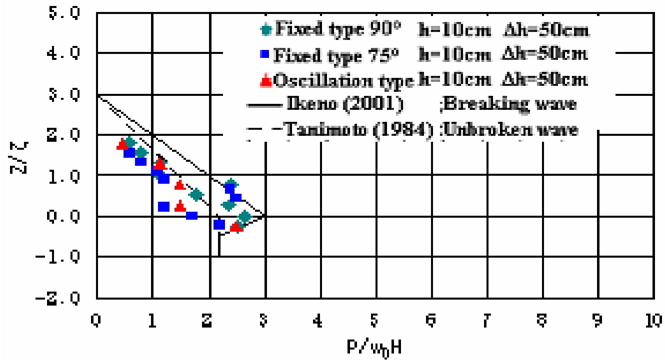

Figure 7 Wave pressure for sustainable wave pressure

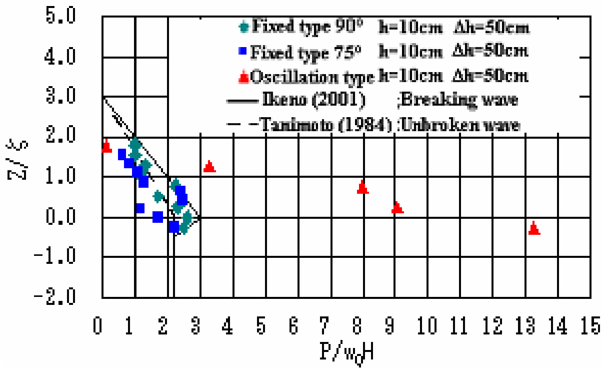

Figure 8 Wave pressure for impulsive force

3. TWO DIMENSION NUMERICAL CALCULATION

3.1 CALCULATION MODELS

The model test results were simulated using numerical analysis that is based on the VOF method: numerical wave channel. As shown in Fig. 9, the experimental flume was modeled into an analytical model. The wave generation point, the flume grade and the gate position are the same as in the model tests. The scale of each element was set at 2 cm by 2 cm, and the total number of model meshes by elements was 35,000. It was decided that in inputting, a flow velocity of constant value is given in the range with specified height and to the horizontal direction at the front surface of the tank. Through trial and error, the flow velocity and height were set so that they equaled the test results for bore wave height and flow velocity at the front of the flap.

3.2 CALCULATION RESULTS

Fig. 10 shows the condition of bore wave propagation within the experimental flume and of bore wave deformation in front of the flap. A bore wave similar to that generated in experimental flume was successfully generated in the numerical wave-motion flume by imparting a flow velocity of 3 m/s at a constant rate in a height range of 20 cm in the front surface of the tank. The current numerical results simulate relatively well the conditions in which the bore wave propagated through the experimental flume. Fig. 11 shows the deformation conditions of a bore wave in front of the flap. The bore wave collides with the flap to form a breaking wave, and then the water mass moves upward to overtop the flap. Large counter-clockwise eddies were formed.

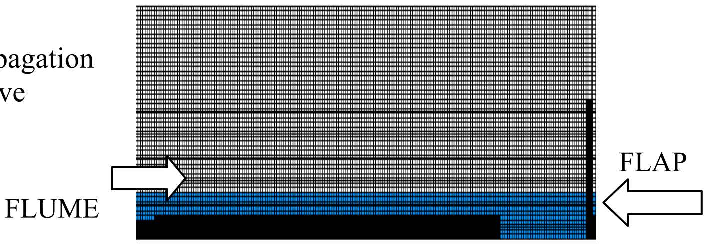

Figure 9 FEM model by VOF method

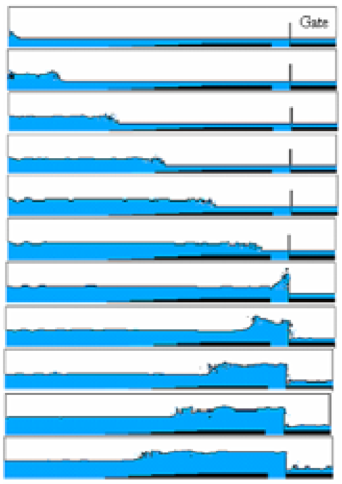

Figure 10 Propagation of wave in flume

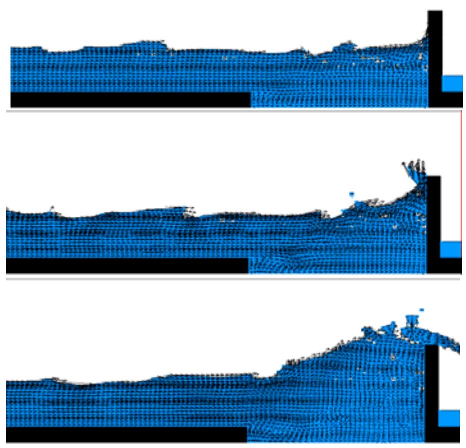

Figure 11 Velocity vector before the gate

Fig. 12 shows a time history of the water level in front of the flap. When the bore wave arrived, the water level reached 55 cm and, after that, nearly 40 cm. The calculated results were similar to the time-history water levels, which had nearly identical bore wave conditions. Fig. 13 shows the calculated time-history results for wave pressure at a wave pressure gauge installed 25 cm from bottom edge of the flap. The results show that the bore wave calculated short-period spike-shaped wave pressure was calculated, and the calculated results did not agree well with the measured results. Fig. 14 shows the vertical wave pressure distribution obtained by numerical calculation. The numerical analytical results based on the VOF method tracked most of the results obtained in the model test, but the local wave pressure values did not conform to the vertical distribution of wave pressure.

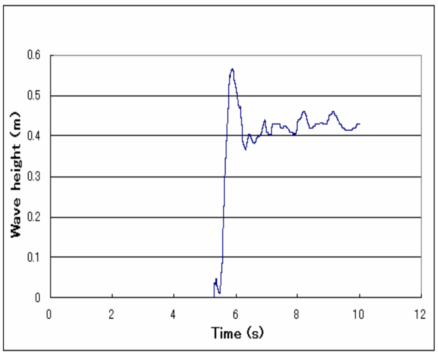

Figure 12 Water height

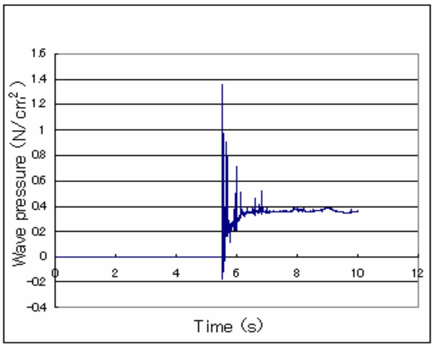

Figure 13 Wave pressure

4. THREE DIMENSION NUMERICAL CALCULATION

4.1 CALCULATION MODELS

Effect of the gate for Tsunami prediction of behavior of Tsunami invasion into the model port as shown in Fig.15 are studied by three dimensional analysis. The calculation model as shown in Fig.16 is done for one of the small port areas where is located at vigorous Tsunami activity area. The location had many Tsunami attack histories. The flap gate with 80m length and 9m height is located at a mouth of the port. The scale of model is 1400mx1200mx47m. Sea area, port area and land area are modeled. Total elements number is 1,680,000 and an element size is 25mx25x1.88m. Boring wave with 2.35m is input at boundary line (right side of Fig.16) and initial average Tsunami wave velocity is 2.03m/s. This input date is calculated another calculation model on Tsunami that is considered by fault movement at sea bed and propagation of Tsunami wave in Pacific Ocean by FEM. Duration time of calculation is 200s. Friction at sea bottom is not considered in this calculation.

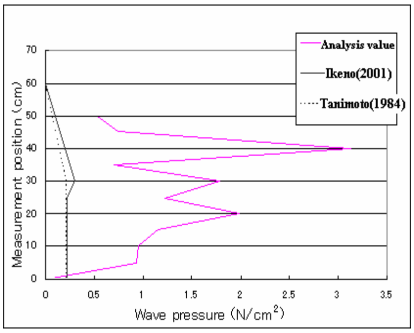

Figure 14 Distribution of pressure

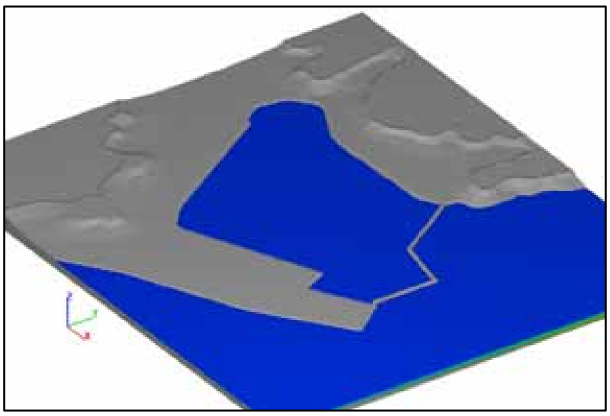

Figure 15 Adopted port area for simulation

Figure 16 FEM model of port area

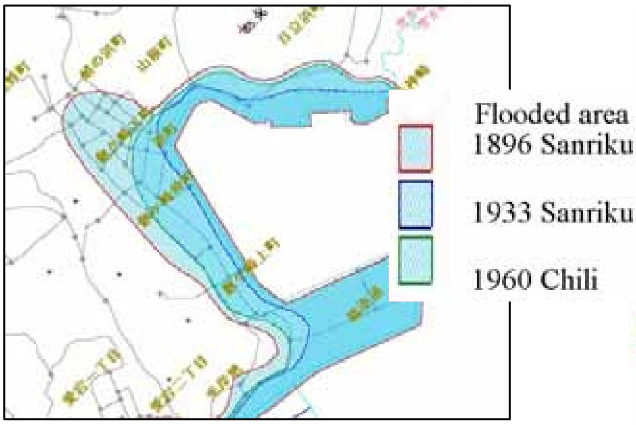

Figure 17 Flooded area for three Tsunamis

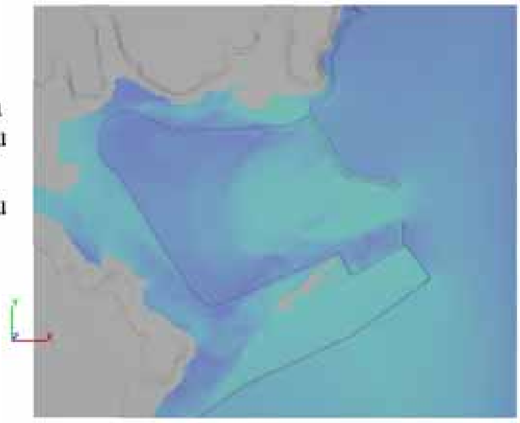

Figure 18 Simulation results for actual Tsunami

To confirm the validity of simulation model, flooded area that was recorded for three historical Tsunamis is compared to the calculation result. Fig.17 shows the flooded area for historical Tsunamis for 1896 Sanriku Tsunami, 1933 Sanriku Tsunami and 1960 Chili Tsunami. Fig.18 shows calculated flooded area. Simulation result almost follows the past flood area.

5.2 CALCULATIN RESULT

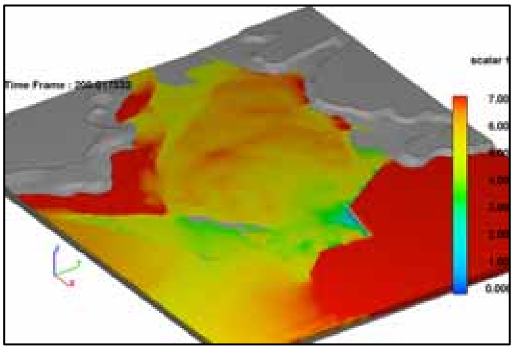

Figure 19 Water level without the gate

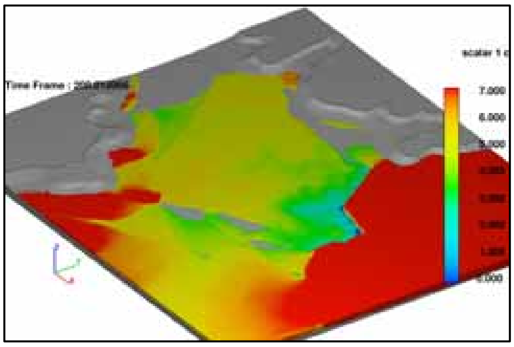

Figure 20 Water level with the flap gate

Fig.19 shows water level in the port area with the gate and flooded area is narrowed rather than the calculation result without the gate as shown in Fig.20.

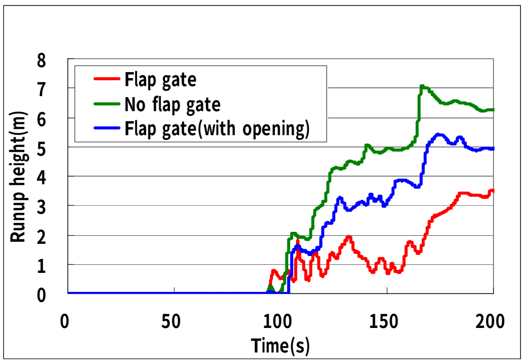

Figure 21 Run-up height at pier

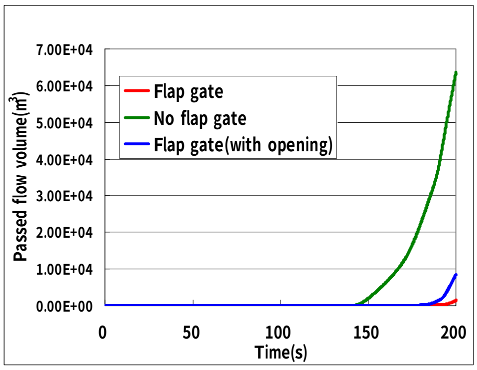

Figure 22 Passed flow volume at boundary

Fig.21 shows run-up height at pier in the port. When the flap gate is not installed, maximum wave height is more than 7m. However, maximum wave height decreases to 3m when the gate is installed. The gate consists of four element flaps with 20m width. Because of maintenance work or any troubles, it is possible that one gate is not closed and Tsunami flows into the port through the opening. In this case, maximum run-up height decreases to 5m. Fig.22 shows passed flow volume through the boundary at west side of the town and the flow volume is very small when the gate is installed.

5. CONCLUSION

The major conclusions were obtained as follows.
1) The flap gate is proposed to protect the populated area from the Tsunami. The flap gate is constructed at the mouth of the port or land space along the coast line. The flap gate is installed at sea bottom. With the arrival of a tsunami, the flap floats upward due to buoyancy and it sinks again after Tsunami attack.
2) The hydraulic properties are studied by model test in flume. In the vertical distribution of sustained wave pressure followed to impulsive wave pressure, no notable differences were observed with regard to flap angle or support system. The distribution wave pressures obtained by model test are smaller than those calculated using the equation proposed by Ikeno, et al. but do agree well with values obtained using the equation proposed by Tanimoto, et al. that does not take breaking waves into account.
3) Results of two dimension numerical analysis based on the VOF method generally tracked the results obtained in the model tests; but the wave pressure in the case of breaking waves in numerical analysis did not agree with the results of the model tests.
4) By three dimension FEM, flooded area, wave run up height etc. are fairly followed to the past Tsunami events for a local port where is located at Tsunami vigorous activity area. The flooded are is limited when the flap gate is installed at mouth of the port.
5) Effectiveness of the flap gate is confirmed by both model test and numerical simulation.

Acknowledgement
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