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EXPERIMENTS OF TSUNAMI FORCE ACTING ON BRIDGE MODELS

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The fourth largest earthquake in the world since 1900 was happened on December 26, 2004, off the west coast of Northern Sumatra, Indonesia. A Japanese group of researchers led by the first author departed to Banda Aceh and surrounding areas. One of the bridges surveyed is Ulee Lheue Bridge in Banda Aceh, near the north coast. The bridge is still functioning although the girders were displaced 35 cm laterally near the abutment. Experimental tests were carried out to measure the hydrodynamic force on a bridge model. Different levels of tsunami amplitude and floating debris were incorporated. The effect of breakwaters in front of the bridge was also studied.

Key Words : *tsunami, force, flow velocity, flow depth, drag coefficient, impact duration, breakwater*

1. INTRODUCTION

The fourth-largest earthquake in the world since 1900 happened on December 26, 2004, at 00:58:53 UTC (or 07:58:53 local time), off the west coast of Northern Sumatra, Indonesia. The magnitude was 9.0, the focal depth was 30 km, and the epicenter is 255 km from Banda Aceh, the nearest provincial capital in Sumatra. The earthquake itself caused some damages and casualties in Banda Aceh and Meulaboh. The subsequent tsunami killed more than 125,468 people, and left 94,550 people missing in Northern Sumatra region.

A Japanese group of researchers led by the first author departed to Banda Aceh and surrounding areas in attempt to study the lessons from the huge earthquake and tsunami. One of the bridges surveyed is Ulee Lheue Bridge in Banda Aceh1), near the north coast, where the tsunami flow depth is estimated as 12 meter. The bridge is still functioning although the girders were displaced 35 cm laterally near the abutment and displaced more near the mid span.

2. ESTIMATED TSUNAMI FLOW VELOCITY FROM BRIDGE DAMAGE

The minimum water velocity causing the bridge to move is predicted by using fluid drag force formula. The formula is shown in Equation (1)2), where ρ_{wtr} is the water density (1000 kg/m^3), C_D is the fluid drag coefficient (taken as 1.0 for a bridge resulted from the experiment), v is the flow velocity, and A is the attacked area of the bridge.

$$F_d = \tfrac{1}{2}\rho_{wtr} C_D v^2 A \qquad (1)$$

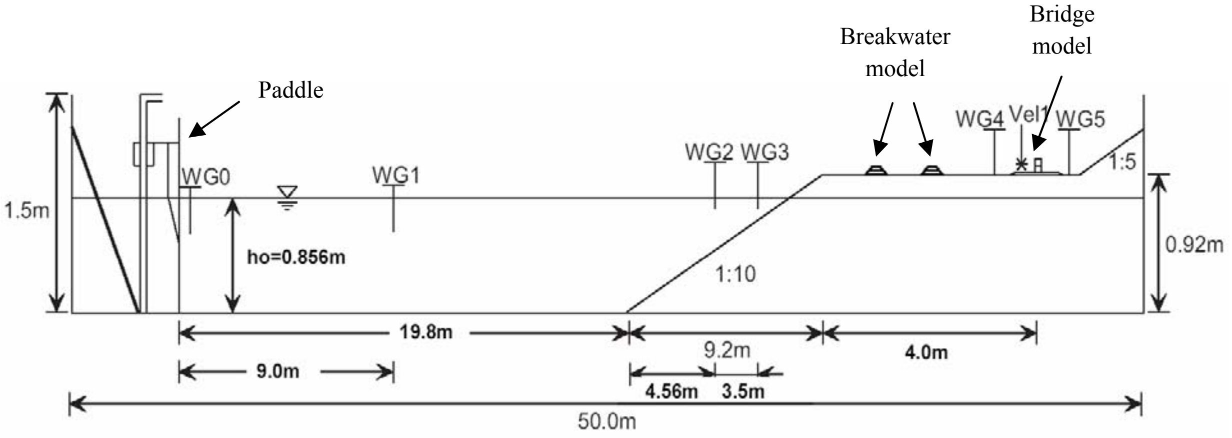


Fig.1 Water Channel and Wage Gages

From the dimensions of Ulee Lheue Bridge$^{1)}$, the attacked area A is calculated as 40.25 m^2 for one span. The volume V of one span containing five girders and one deck is calculated as 123.7 m^3. The mass m is calculated as $V\times\rho_{\mathrm{con}}$ = 123.7×2,500 = 309,250 kg. The weight W is calculated as $m\times g$ = 309,250×9.8 = 3,030,650 Newton.

Considering water buoyancy at the bridge, the weight with bouyancy is calculated as $W' = W - V\times\rho_{\mathrm{wtr}}$ = 3,030,650 − 123.7 ×1,000 = 2,906,950 Newton. The bridge resisting force caused by friction is calculated as $W'\times\mu$ = 2,906,950 × 0.3 = 872,085 Newton. Minimum water drag force is the same as the bridge friction force, therefore the minimum water velocity is calculated as:

$$v = \sqrt{\frac{872{,}085\times 2}{1000\times 1.0\times 40.25}} = 6.58\ \mathrm{m/s} \approx 23.7\ \mathrm{km/h} \qquad (2)$$

The real velocity of the tsunami flow with depth of 12 meter should be larger than this value because the bridge is not perpendicular to the tsunami flow direction.

3. EXPERIMENT OF TSUNAMI FORCE ON BRIDGE

In order to study the force exerted by tsunami flow and debris on a bridge structure, experimental tests were carried out. Set up of the experiments is shown in Fig. 1. Water channel of 50 meter length is used in the experiments. Sloping bottom of 1:10 originated 19.8 meters from the paddle was built. Tsunami amplitudes were measured at WG1, WG2, and WG3. Still water depths at WG1, WG2, and WG3 are 85.6cm, 40.0cm, and 5.0 cm, respectively. Distance between WG1 and WG2 is 13.7 meter, and distance between WG2 and WG3 is 3.5 meter.

The setting of the bridge model is shown in Fig. 2.

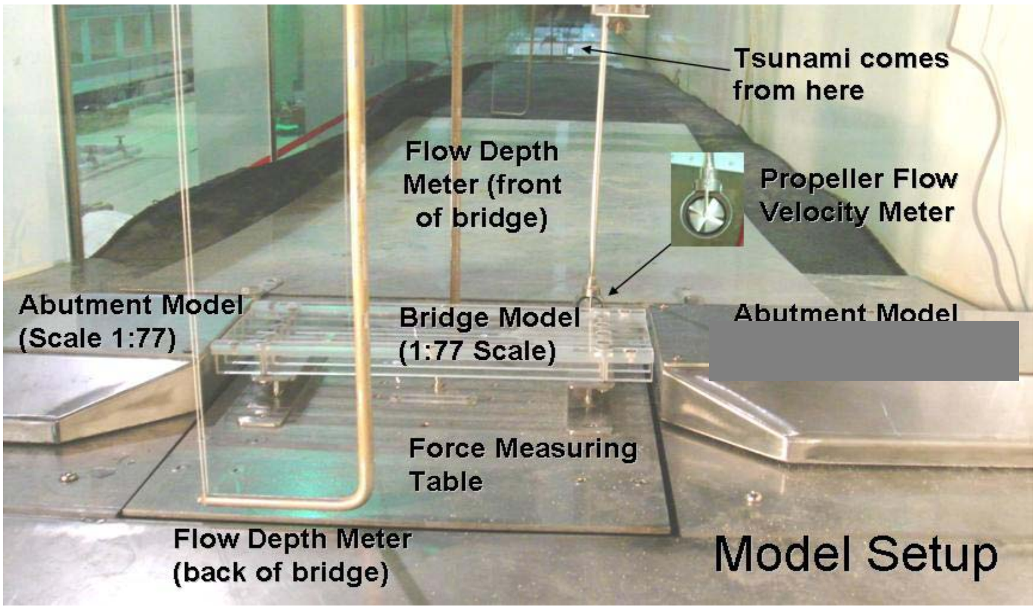


Fig.2 Bridge Model Set Up

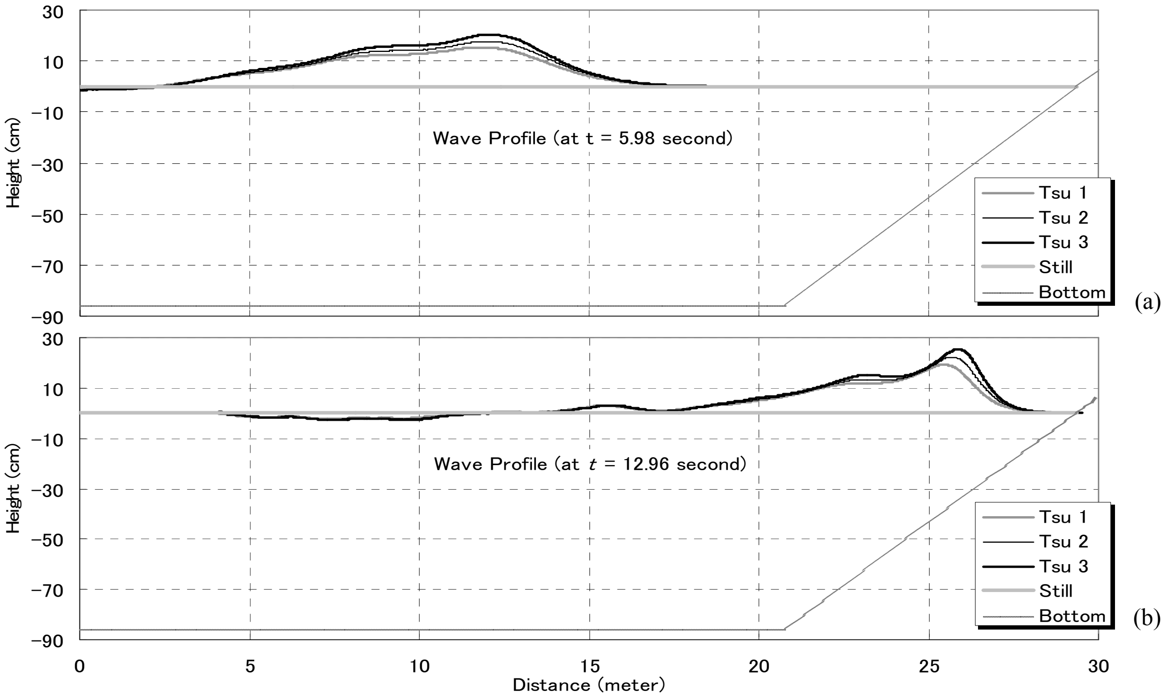


Fig.3 Tsunami profiles at different times and levels

Propeller type flow velocity meter is put in front of the bridge model. Flow depth meter are placed in front and rear of the bridge model. The bridge model is connected to the force-measuring table. Under the force measuring table, a load cell is used to measure the force exerted by the table and the bridge model.

Coarse tsunami profiles were drawn based on wave celerity. The wave celerity was based on wave arrival time and distance between wave gages. The coarse profiles are shown in Fig. 3. The maximum amplitudes at 9.1 meter before sloping bottom are 15.2 cm, 17.6 cm, and 20.3 cm, for tsunami levels 1, 2, and 3, respectively (Fig. 3(a)). The maximum amplitudes at 4 meter before shoreline are 19.1 cm, 22.0 cm, and 25.2 cm, for tsunami levels 1, 2, and 3, respectively (Fig. 3(b)). The generated tsunami profiles just before they reach the beach are shown in Fig. 4. The maximum amplitudes at 5 cm before shoreline are 18.6 cm, 21.0 cm, and 24.2 cm, for tsunami levels 1, 2, and 3, respectively.

Fig. 5 shows the sequence of photographs when a tsunami flow hit the bridge model. The time history of flow velocity, depth, and force were recorded.

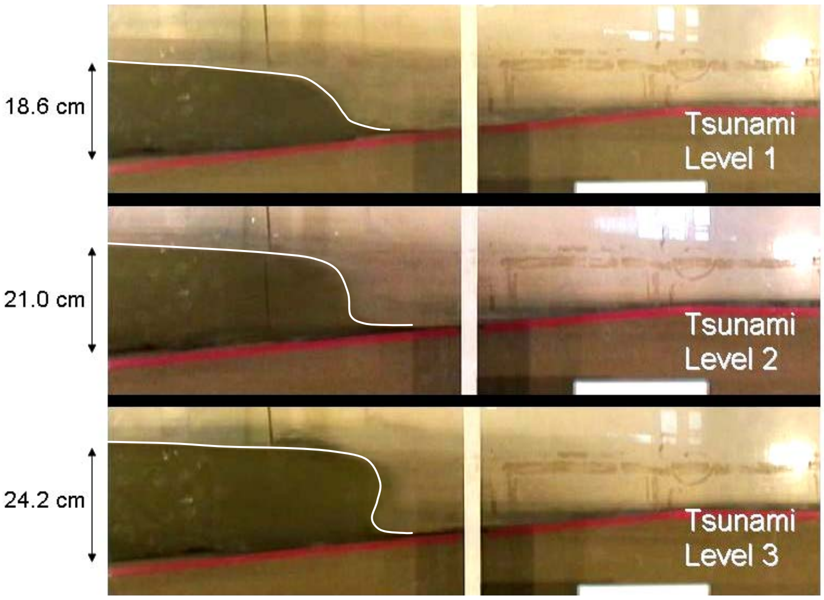


Fig. 4 Tsunami profiles near beach

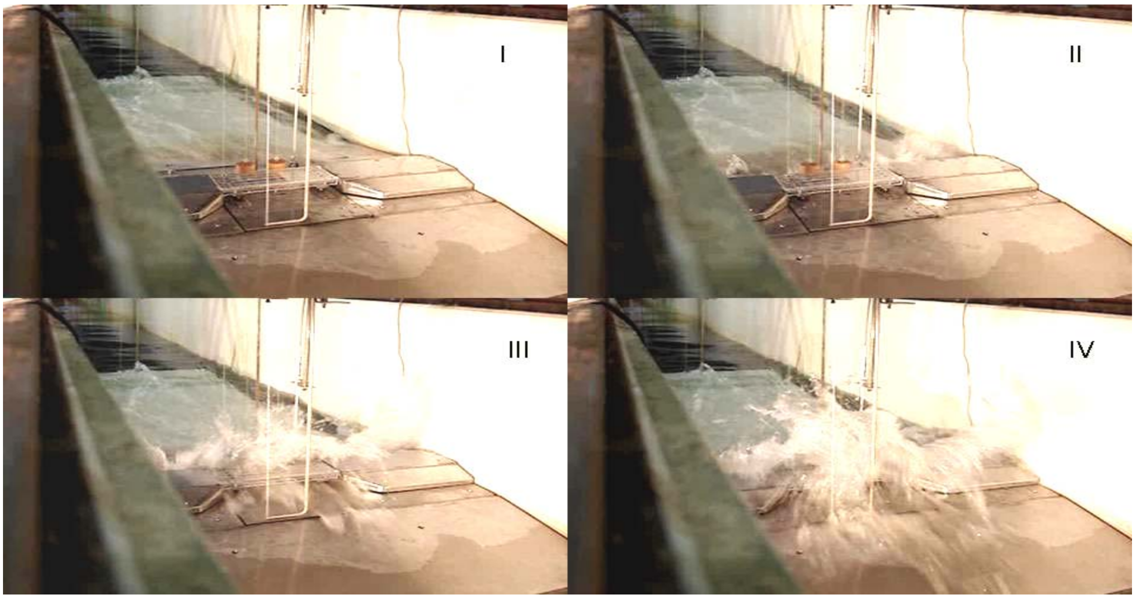


Fig. 5 Tsunami flow hits the bridge model

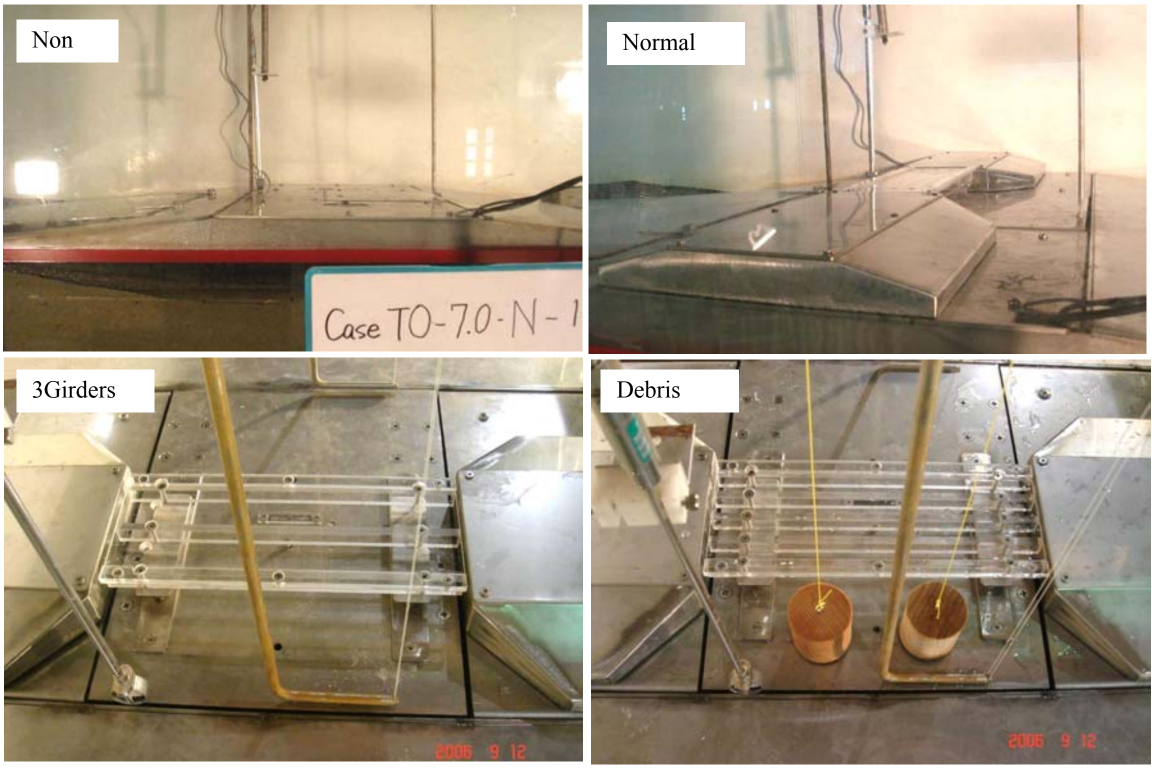


Fig. 6 Four Cases Studied

There are four cases studied. They are: *Non*: no bridge and abutment model at the force-measuring table; *Normal*: bridge and abutment model at the force-measuring table; *3Girders*: as *Normal* case but the girders are three instead of five. *Debris*: bridge and abutment model plus hanging wooden cylinders in front of the bridge. The cases are shown in Fig. 6.

Bridge model (24 mm high, 300 mm long, 120 mm wide; 460 grams; 365.4 cm^3) is made of acrylic glass (deck: 300×120×4 mm^3; girders: 300×16.5×8 mm^3×5; railing: 300×13×3mm^3). The size is 1/77 of the Ulee Lheue Bridge. Flow attack area is 72 cm^2.

The pier model connecting to the force-measuring table is of stainless steel weighing 540 grams. The table connecting to the load cell is weighing 3,670 grams. The bridge model system is weighing a total of 460 + 540 + 3,670 = 4,670 grams.

The debris models are made of wooden cylinder with diameter of 5 cm and height of 5 cm. The shape was chosen for the debris to easily hit the

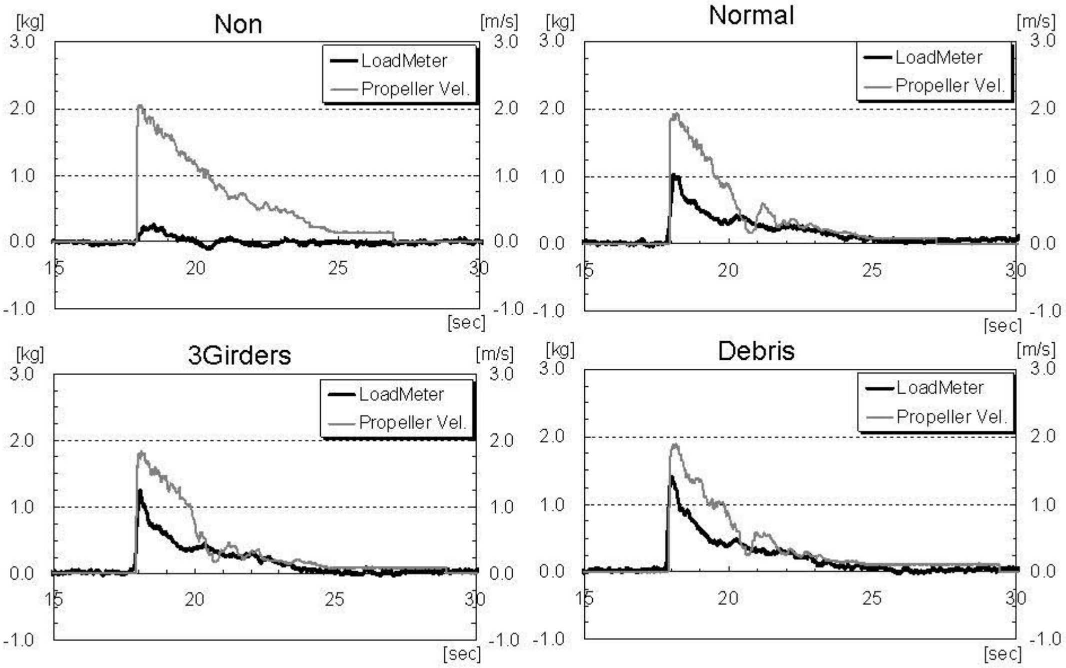


Fig. 7 Velocity and force time history for tsunami level 1
(multiply by 9.8 m/s^2 to approximate force in Newton)

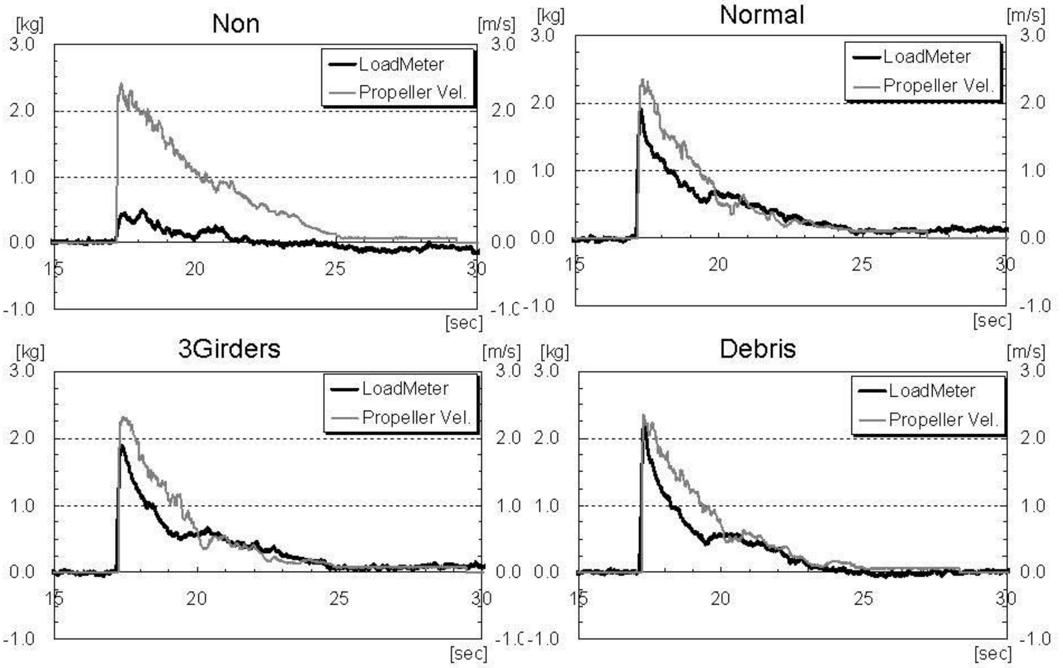


Fig. 8 Velocity and force time history for tsunami level 3
(multiply by 9.8 m/s^2 to approximate force in Newton)

bridge at the same time during the tsunami simulation experiments. Two debris models (with total weight of 155 grams) were incorporated.

4. RESULT OF TSUNAMI FORCE ON BRIDGE

Time histories of flow velocity and force for tsunami level 1 at different cases are shown in Fig. 7. The force starts with sudden large force followed by gradually diminishing force. The velocity profiles also show similar path. The time history for tsunami level 3 and different cases are shown in Fig. 8.

The maximum force and velocity occurred at about the same time. Relation between maximum velocity and maximum force were plotted (Fig. 9). The maximum velocity was the average result of “no bridge and no abutment” (Non) case.

In real cases, the velocity is predicted by method in Chapter 2. Other examples are by run up height, scene video, or tsunami flow depth[5)].

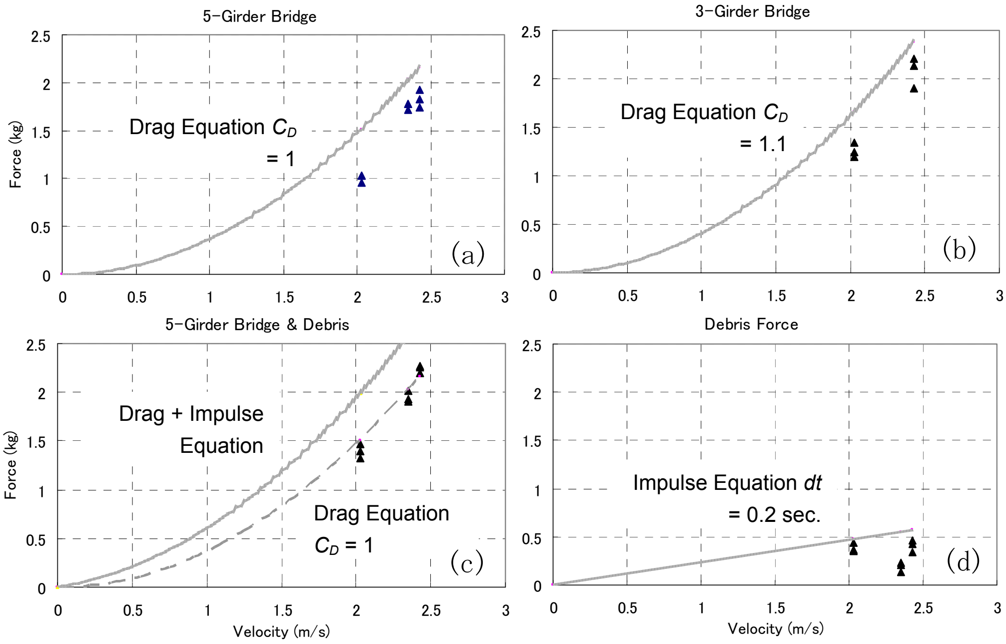


Fig. 9 Correlation between maximum force and maximum velocity (multiply by 9.8 m/s^2 to approximate force in Newton)

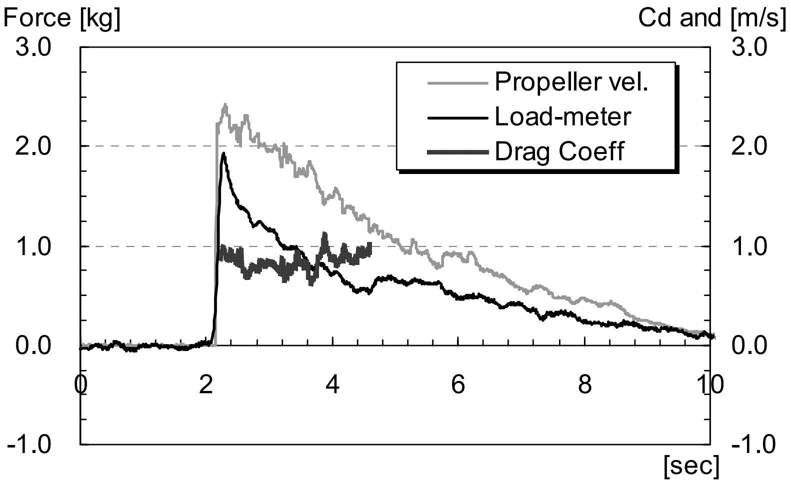


Fig. 10 Typical drag coefficient for normal case (tsunami level 3) (multiply by 9.8 m/s^2 to approximate force in Newton)

Forces obtained by using drag equation (Equation (1)) with drag coefficients equal to 1.0 and 1.1 are also plotted. Drag coefficient equals to 1.1 is sufficient to estimate the force due to tsunami flow on the bridge model.

Time history of drag coefficient is in Fig. 10. It shows that the drag coefficient is relatively constant during the attack. The force becomes smaller when the velocity becomes smaller.

Drag coefficient, in general, depends on the Reynolds number, if the numbers is below 10,000. At higher numbers, the drag coefficient for most geometries remain essentially constant[2]. The flow at high number becoming fully turbulent. The dimensionless Reynolds number is specified in Equation (2), where V_{avg} is average flow velocity, D is geometry characteristics (assumed to be the depth of the tsunami flow on land, h), and μ is dynamic viscosity of water (1.002×10^{-3} kg.s/m at 20 °C).

For tsunami level 1 at the location of the bridge model (3.9 m from shore), with average velocity of 2.02 m/s and depth of 5.86 cm, the average Reynolds number is 117,899, which shows the flow is fully turbulent. Similar calculation for tsunami level 3 shows Reynolds number of 182,703. Therefore, the drag coefficient above can be used for larger geometry under tsunami attack since tsunami flow is also turbulent.

$$\mathrm{Re} = \frac{\rho V_{avg} D}{\mu} = \frac{998.0\times 2.02\times 0.0586}{1.002\times 10^{-3}} = 117899 \qquad (2)$$

Three-girder bridge model results in larger force than five-girder bridge model. The reason will be discussed in the dynamic behavior of the model

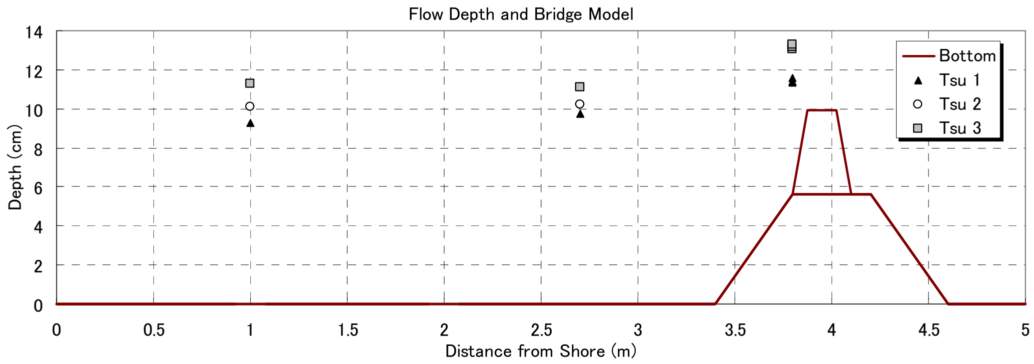


Fig. 11 Flow-depth as a function of distance from shore

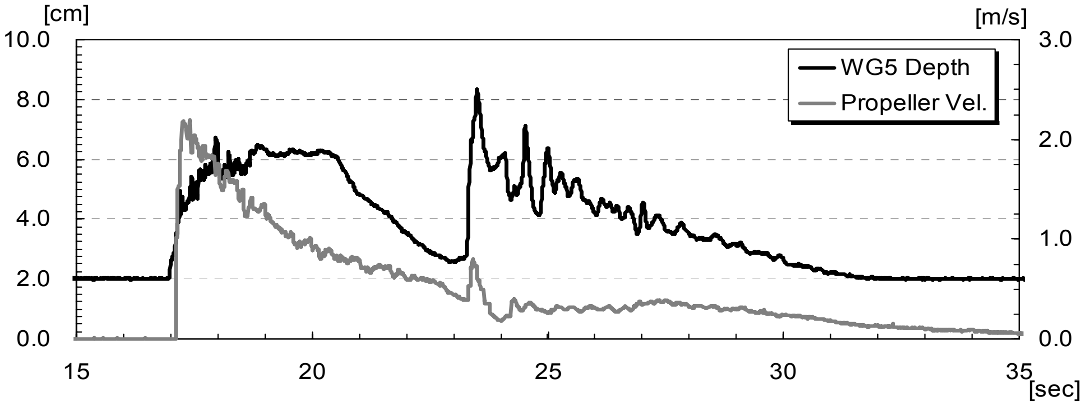


Fig.12 Time history of flow depth and velocity (2.7 m from shore, Tsunami level 1)
The depth gage is at 2 cm above the ground

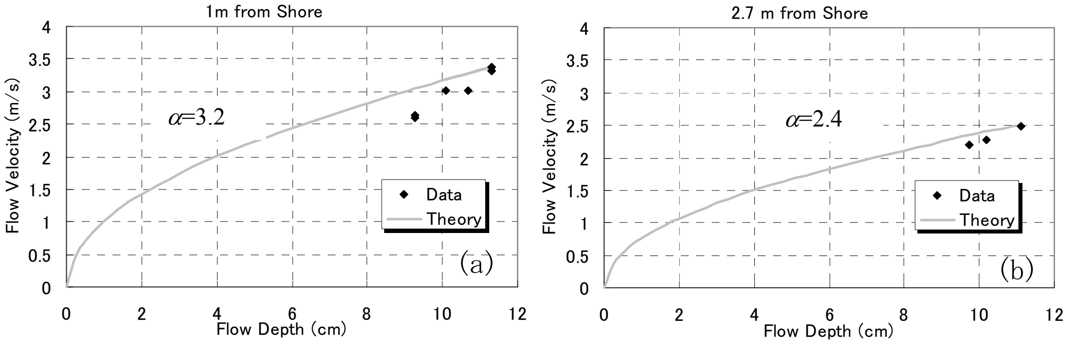


Fig. 13 Relation between flow depth and velocity (a) 1.0 meter from shore and (b) 2.7 meter from shore

below.

Figure 9(c) shows the force by water and floating debris. The debris impact force shown in Figure 9(d) is forces in Figure 9(c) subtracted by forces in Figure 9(a). In the figure, a curve showing impulse equation based on impact time *dt* of 0.2 second is shown. The equation is[3)]:

$$F_I = \frac{mv}{dt} \qquad (3)$$

From the figure, impact duration of 0.2 second is appropriate in predicting the force in the experiments. In reference[3)], the value of *dt* equals to 0.2 – 0.4 seconds for reinforced concrete walls is also recommended.

5. TSUNAMI FLOW VELOCITY AND DEPTH

Fig. 11 shows the flow depth as a function of the distance from shore. Also shown in the figure are the abutment and bridge model elevation, and the force measuring table elevation. The flow depth tends to decrease as it goes further inland. The velocity also decreases, probably due to energy dissipation by the ground surface during the flow.

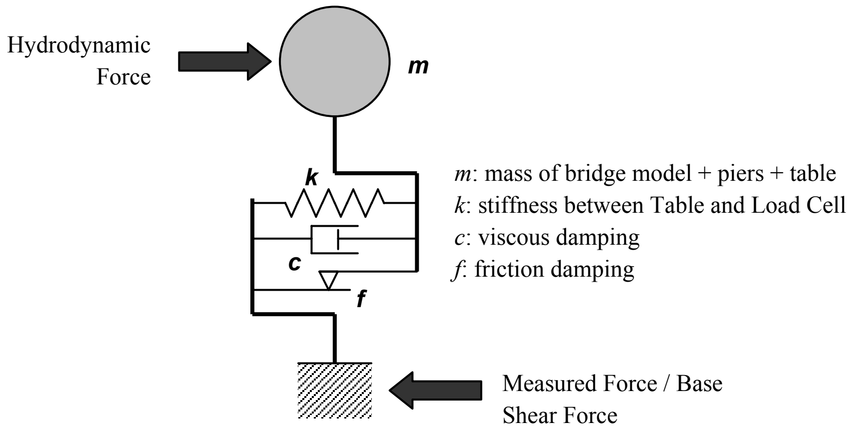


Fig. 14 Dynamic model of the experimental system

Fig. 12 shows the time history of flow velocity and depth. Maximum velocity happens at the beginning of the attack whereas the maximum flow depth happens some times after the maximum velocity. This shows the profile of the tsunami water on land naturally has the lower depth in front and higher depth in the middle part.

Fig. 13 shows the relation between flow depth and flow velocity. Given the same flow depth, near shore velocity (1.0 meter from shore) is larger than that of far from the shore (2.7 meter from shore). The ground level is the same in both cases.

Assuming the velocity is a function of gravitation acceleration g and depth h as shown in Equation (4)[4], the coefficient α is obtained.

$$v = \alpha\sqrt{gh} \tag{4}$$

Coefficient α is a function of maximum run-up height[4] and energy loss. In this experiment, the maximum run-up height was not measured since the ground is horizontal. The energy loss of the flow is seen from the smaller α when the distance from shore is larger.

6. INFLUENCE OF MODEL MASS

Since the measurement of tsunami force was by using a load cell placed as the base of the model, it is important to check the dynamic properties of the model system. The system can be modeled as shown in Fig. 14.

From the system model, the mass, the flow velocity, and the measured force are known. The unknowns are the stiffness k and the damping

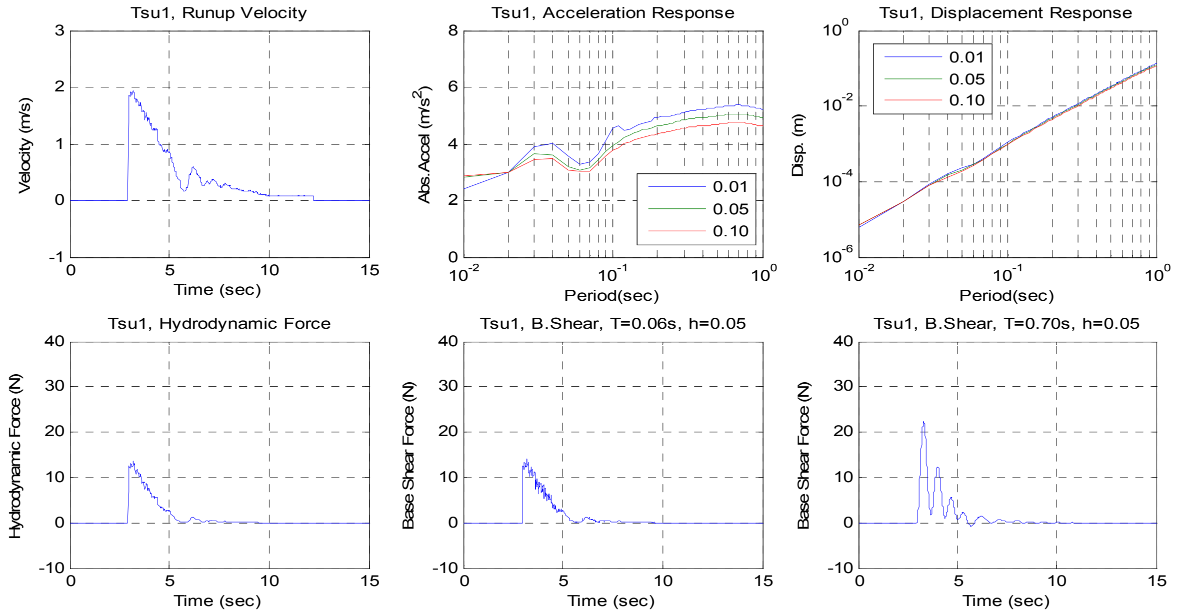


Fig. 15 Flow velocity, hydrodynamic force, and responses of the model

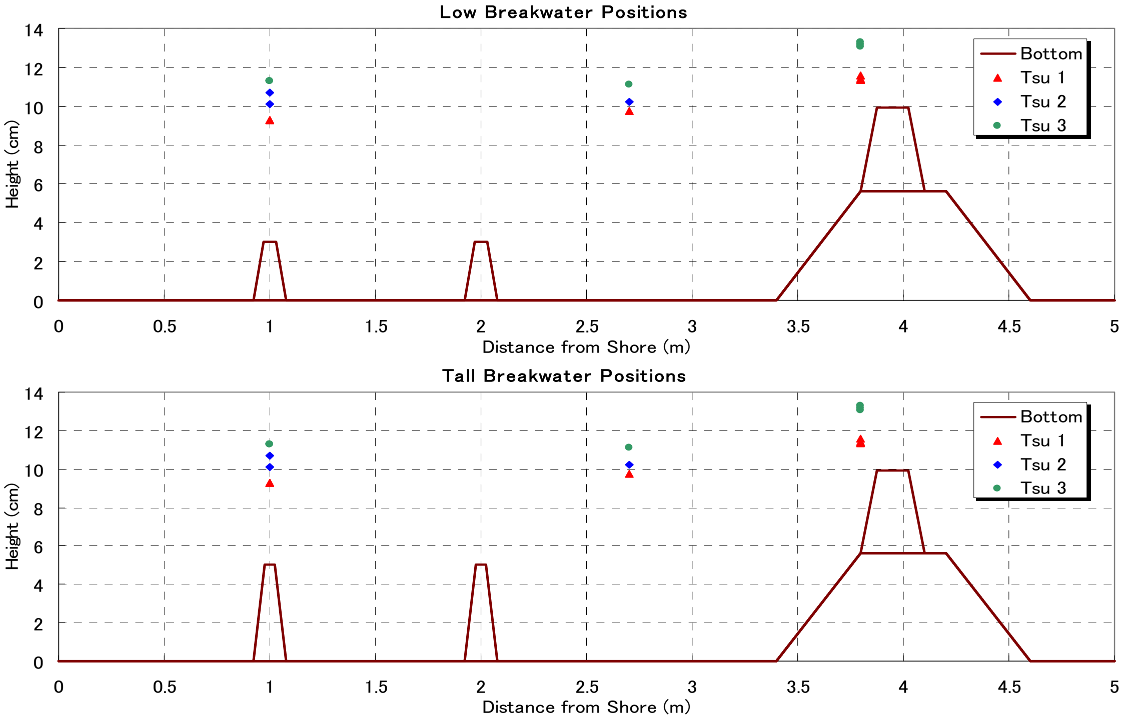


Fig. 16 Breakwater position in front of bridge model

coefficient c (the friction coefficient f is assumed to be small and therefore is included in the c). From the flow velocity time history of tsunami level 1 (Fig. 15(a)), the hydrodynamic force is obtained (Fig. 15(d)) by using Equation (1) and $C_D = 1$. Based on the force time history, the response spectra of the model with natural period from 0.01 to 1.00 second are obtained (Figs. 15(b) and 15(c)).

The plots of the base shear at a natural period of 0.06 and 0.70 seconds are shown in Figs. 15(e) and 15(f). From the figure it is clear that the smaller the natural period, the better measurement can be obtained. Fig. 15(e) shows almost similar shape to Fig. 15(d). This means the response measured at the base of the model is almost the same as the input force. On the other hand, if the model is too flexible (Fig. 15(f)), the response is higher than the input force. Since the measured force in the experiment did not show any resonance as shown in Fig. 15(f), the experimental system is assumed to be stiff enough for accurate measurement.

The above study explains the result of the force measured at the three girder bridge model is larger than that of the five girder one. The three girder bridge model is more flexible than the five girder one. Because of the flexibility, the force measured at the base of the model shows bigger value that the force exerted by the tsunami flow. It shows that the stiffer the model the better the result if the hydrodynamic force is to be measured at the base of the model.

7. EFFECT OF BREAKWATER IN FRONT OF BRIDGE

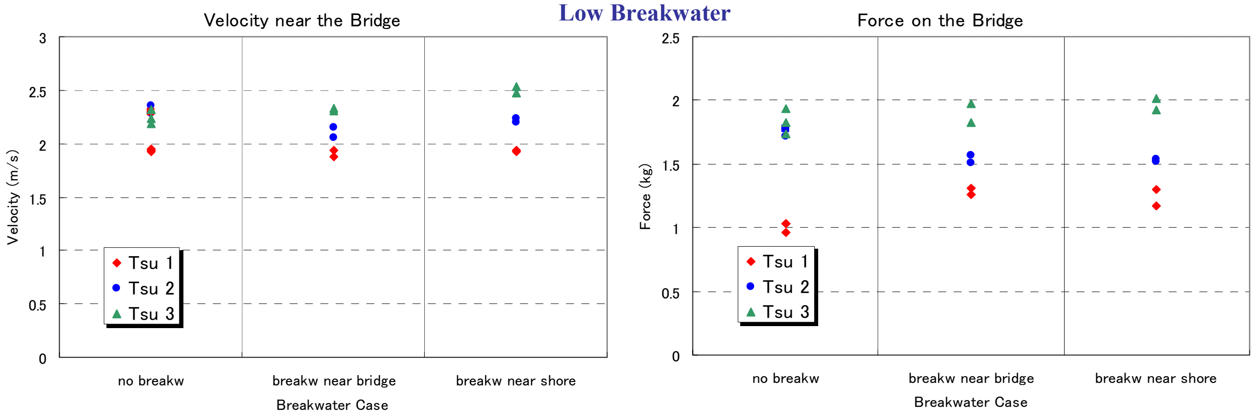
The effect of breakwaters in front of the bridge model were also studied. The breakwaters represented the ones being built in Banda Aceh along the north coast. The height is about 2.5 meter. It is made of stones and has less than 45° slopes.

The set up of the experiment is as shown in Fig. 16. There are four cases in the experiment: (1) low breakwater at 1 meter from shore, (2) low breakwater at 2 meter from shore, (3) tall breakwater at 1 meter from shore, and (4) tall breakwater at 2 meter from shore. The ones at 2 meter from shore are named “near bridge position”. The location of the bridge and the measuring table is shown at 4 meter position.

The low breakwater has the height of about 1/3 of the tsunami flow height. Whereas for the tall breakwater, the height is about 1/2 of the height of the tsunami flow height.

The low breakwater does not reduce much the velocity and force to the bridge (Figs. 17(a) and 17(b)). Tall breakwater is relatively effective in reducing the flow velocity (Fig. 17(c))., although the force was not clearly reduced (Fig. 17(d)). The reason is that the models have relatively smooth surface and 45° slopes. During the experiment, the water just jumped, dropped, and continued flowing without loosing much energy.

Low Breakwater



Tall Breakwater

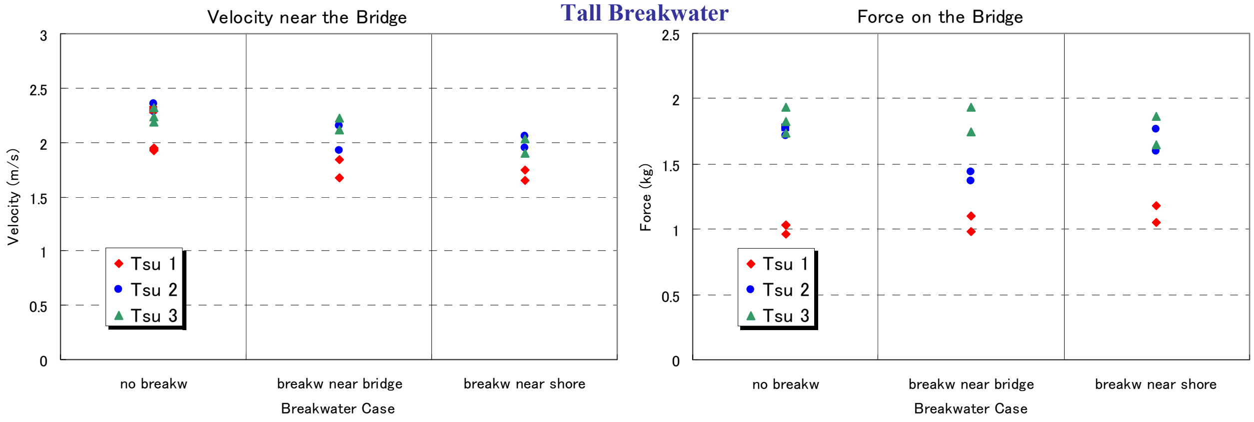


Fig. 17 Effect of low and tall breakwater on the flow velocity and force

8. CONCLUSIONS

The experimental results show that tsunami force to the bridge starts with large value of force and gradually reduces to smaller ones.

The largest force happened at the largest velocity which is also at the beginning of the attack. Based on largest velocity and force, the drag coefficient of the bridge model is found to be 1.1. Since the flow in experiment is turbulent, the drag coefficient is also applicable for larger body under turbulent flow, as in the case of tsunami flow.

Impact duration of 0.2 second is appropriate for predicting impact force by floating wooden debris. This value is also recommended by FEMA55 for reinforced concrete walls.

From the dynamic analysis of the model, the load cell under the bridge model is able to measure the hydrodynamic force appropriately as long as the connection between the model and the load cell is stiff.

Low breakwater (about 1/3 of tsunami flow height) does not significantly affect the flow velocity. Tall breakwater (about 1/2 of tsunami flow height) is starting to be effective in reducing flow velocity.

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REFERENCES:

1) Iemura, H., Pradono, M. H., and Takahashi, Y.: Report on the Tsunami Damage of Bridges in Banda Aceh and Some Possible Countermeasures, 第28 回土木学会地震工学研究発表会, 東京工業大学大, August 22 – 24, 2005.
2) Cengel, Y. A. and Cimbala, J. M.: *Fluid Mechanics, Fundamentals and Applications*, McGraw Hill, 2006.
3) FEMA55: Chapter 11 Determining Site Specific Loads, *Coastal Construction Manual*, Vol. 2, 2006.
4) Yeh, H.: Maximum Fluid Forces in the Tsunami Runup Zone, *Journal of Waterway, Port, Coastal, and Ocean Engineering,* ASCE, Vol. 132, No. 6, November 1, 2006.
5) Matsutomi, H., Sakakiyama, T., Nugroho, S., Matsuyama, M.: Aspects of Inundated Flow Due to the 2004 Indian Ocean Tsunami, Coastal Engineering Journal, Vol. 48, No.2, pp. 167-195, 2006

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