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SIMULATION OF TSUNAMI FORCE ON ROWS OF BUILDINGS IN ACEH REGION AFTER TSUNAMI DISASTER IN 2004

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ABSTRACT

After the Indian Ocean Tsunami 2004 in Aceh, houses and other buildings were reconstructed by government and *Non-Governmental Organizations* (*NGO*). The new buildings near the coastline are open directly to similar tsunami attack. The layout of such new residential are normally arranged and aligned as rows of buildings. The front rows of the buildings suffer more tsunami force due to their location that are closer to the beach and the effect of the reflection from the adjacent buildings. This research aims to analyze the tsunami force on buildings of different types, and the effect of other buildings nearby. The research was conducted using a physical model at the Hydraulic and Hydrology Laboratory, Research Centre for Engineering Science, Universitas Gadjah Mada Indonesia. The physical model simulations were carried out in a flume of 24 m long, 1.45 m wide, and 1.5 m high, that was facilitated with tsunami generator based on dam break system. The models of the buildings were made of plywood and were placed in a row perpendicular to the flume. The distance between the buildings was varied to observe the effect of the gaps. The results show that the force on the building depends on the gap between the buildings. Although the effect of the gap was more significant on low buildings, the effect of force on high buildings was more sensitive to the change of the gap size. Simple equation for practical use is proposed to calculate the tsunami force on building with the effect of nearby buildings.

Keywords: *Tsunami; building; force; pressure, gaps; openings, simulations*

1 INTRODUCTION

The huge Indian Ocean Tsunami in 2004 has caused severe damage to infrastructures and loss of lives. Aceh, a province of Indonesia, suffered the greatest losses in this catastrophe. The incident has made Aceh people realize that they are vulnerable to tsunamis. After the tsunami disaster, Aceh once again was struck by a tsunami in the area of Simeulue and Nias Islands on 26 March 2005. Another earthquake measuring over 8 on the Richter scale occurred in Aceh on 11 April 2012, which resulted in a low tide in Ulee Lheue Beach Banda Aceh. Although no tsunami was generated, it has made Acehnese became more prepared against such horrible hazards.

Takahashi et al, (2007) classified the level of damage of buildings in Aceh into four districts. In District 1, which is the coastal area, almost the entire buildings in the region were completely destroyed by the tsunami. A lot of new buildings were built in this area during the reconstruction. These new residential areas, schools, hotels, and industrial areas are directly open to the sea (Figure 1) especially when coastal forests that serve as buffer zones are no longer available due to the 2004 tsunami.

A coastal forest is an alternate natural measure to reduce the tsunami hazard but it needs considerable time to grow and achieve the required strength so as to function properly. Proper arrangement of buildings at coastal areas may contribute to reducing the damage caused by tsunami. For instance, such layout is needed in order to provide protection to weaker buildings by properly designed stronger buildings. For example, the weaker houses were those of tsunami victims that were built by the government and Non-Government Organizations (NGOs).

Unfortunately, with the present arrangement, many of the houses would be the first to be damaged by the force of tsunami waves. When the weaker buildings are destroyed or are lifted up by the tsunami, they may be brought further inland as debris, hit other buildings, and thus create more damage and greater losses of lives. Houses that were built close to each other as shown in Figure 2 may obstruct tsunami flows, which subsequently may increase the tsunami force upon them. A number of formulae are available for computing the tsunami force on either piles or walls for example USAEWS (1990). Asakura (2002), Triatmadja and Nurhasanah (2012). Nakano (2010) proposed the computation of force on relatively low building by waves which may overtop them. However, the available formulas do not take into account the effect caused by buildings nearby. In this paper, the effect of the layout of the buildings, especially the distance between the building and the nearby buildings or the size of the gaps relative to the size of the buildings, were studied.

Figure. 1. View of new buildings after reconstruction around the coastal area of Ulee Lheue Banda Aceh. The houses are recently built for tsunami victims (taken from newly built escape building on January 2013).

Figure 2. View of some new buildings after reconstruction in a coastal zone in Banda Aceh.

2 LITERATURE REVIEW

2.1 Tsunami front speed

According to FEMA (2005), tsunami flow depth is generally shallower than the depth of normal flow such as rivers at the same flow rate. Tsunami surge speed on land may be described by Eq. (1)

$$U = k\sqrt{gh}. \tag{1}$$

where U is celerity of tsunami, g is the gravitational acceleration, and h is the surge depth or surge height. The coefficient k represents the surge Froude number (F_r). The surge Froude number that is suggested by FEMA (2005) is approximately equal to 2. The surge speed due to dam break at a non-zero downstream depth is hardly affected by friction bed as suggested by Eq. (2) following Chanson (2005).

$$\sqrt{\frac{h_0}{h_3}} = \frac{1}{2}\frac{U}{\sqrt{gh_3}}\left(1 - \frac{1}{X}\right) + \sqrt{X}. \tag{2}$$

where $X = \frac{1}{2}\left(\sqrt{1 + 8\frac{U^2}{gh_3}} - 1\right)$ and h_3 is the initial of downstream water depth, with $\frac{h_0}{h_3} = X$, and h is the surge height or depth.

Triatmadja and Nurhasanah (2012) indicated that obstacles such as buildings might hinder tsunami flows and create backwater or higher water depth upstream of the obstacles. In such situation, it may be expected that the obstacles themselves are subject to higher tsunami forces. The force on single building may be calculated based on many available formulas, however the maximum force acting on a group of buildings may depend on the layout of the buildings and the surrounding environment. This is discussed in the following section.

2.2 Tsunami force on a vertical wall

The first force that hits a building is the impact force. The force could be very large and may be written as

$$F_i = C_i\rho AU^2. \tag{3}$$

where C_i is the impact coefficient that depends on the shape of the surface of impact and the angle of impact. The drag force of wave on the building follows Eq. (4) (Dean and Dalrymple, 1984).

$$F_D = \frac{1}{2}C_D\rho AU^2. \tag{4}$$

where C_D is the drag coefficient, A is the projected area, and in this case, U is the velocity. The value of C_D depends on the Reynolds number and the shape of the building. FEMA P-55 (FEMA, 2005) recommended that $C_D = 2.0$ for a rectangular pile and that $C_D = 1.2$ for a circular pile. Instead of using U, the surge height is preferred for its availability and ease of measurement. USA-EWES and CERC (1990) and Asakura *et al.* (2002) suggested that surge force follows Eq. (5).

$$F = 4.5\rho g h^2 \tag{5}$$

Eq. (5) implies that the building should be higher than three times the surge height (*h*) so as not to be overtopped by a tsunami. Such building may be called "high building". In a certain situation where the tsunami wave height is almost the same as the building's height, such as those in Aceh, the tsunami may overtop the building and Eq. (5) should not be used. Such overtopped building is hereafter called "low building". The constant, which is 4.5 in Eq. (5) may vary considerably with the distance of the surge from the shore. Triatmadja and Nurhasanah (2012) suggested the use of Eq. (2) with C_f as the combination of both impact and drag forces as in Eq. (6).

$$F_i = C_f \rho A U^2. \tag{6}$$

where C_f varies from 0.6 to 1.03 for low buildings and high buildings respectively.
Based on Triatmadja and Nurhasanah (2012), to accommodate the effect of openings within the building, the force on the building with openings can be written as:

$$F = C_f \rho (1 - n^2) B h U^2. \tag{7}$$

where *n* is the porosity(opening). In this case, C_f is also expected to vary with the layout of the partitions within the buildings.

For a high building an analytical approach of simplified problem may be carried out as follows. The tsunami wave's front height and velocity are assumed to be uniform. When a tsunami wave hits a wall, the water level upstream of the wall may be calculated using the Method of Characteristics as indicated in Figure 3. The solid wall represents row of buildings without gaps.

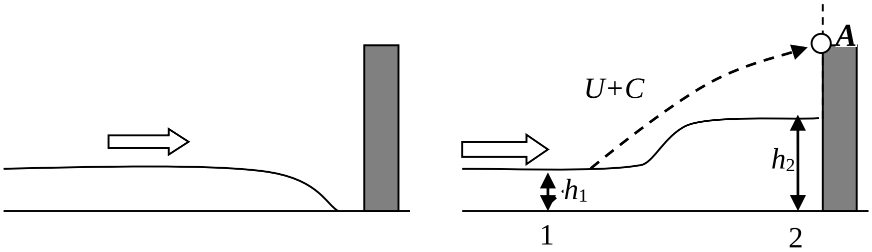


Figure.3. (a) Tsunami surge approaches vertical wall, (b) Tsunami surge hit the wall and was reflected.

At the point A in Figure 3, it follows that

$$U_1 + 2C_1 = U_2 + 2C_2 \tag{8}$$

where $C_n = \sqrt{g h_n}$. Assuming that U_2 equals zero when there is no space or gap between the buildings, Eq. (8) may be written as:

$$F_{r_1}\sqrt{gh_1} + 2\sqrt{gh_1} = 2\sqrt{gh_2}$$

or

$$\frac{h_2}{h_1} = \left(\frac{F_{r_1}+2}{2}\right)^2 \tag{9}$$

The subscripts denote the location of measurements. Since the velocity exactly in front of the building is zero, the force on the buildings may be written as:

$$F = \frac{1}{2}\rho g\left(\left(\frac{F_{r_1}+2}{2}\right)^2 h_1\right)^2 \tag{10}$$

For F_r=2, $F = 8\,\rho g h_1^2$, or simply $F = 8\,\rho g h^2$ which is 77% more than that of Eq. (5). The gap between the buildings enables the tsunami to flows through where U_2 becomes greater than 0 resulting in reduced h_2 and the force on the buildings subsequently.

3 EXPERIMENTAL SET-UP

Physical experiments were conducted in a wave flume of 24 m long, 1.45 m wide and 1.5 m high. The flume was divided into two sections with the upstream part served as the reservoir for generating a tsunami while the downstream part was used to simulate tsunami propagation and tsunami force on buildings. The gate that separates the flume was equipped with a quick release mechanism. The flume was also equipped with a pump to fill the reservoir and an outlet to drain the downstream part of the flume. The experimental setup in this research was similar to the physical model used by Triatmadja and Nurhasanah (2012).

With the above arrangement, a dam break surge may be generated to imitate a tsunami wave. This was carried out by opening the gate quickly. In order to measure the surge front celerity, a series of wave recorders were installed at selected stations (Sta). The distance between the adjacent stations, from Sta 1 to Sta 4, was 1 m, as depicted in Figure 4.

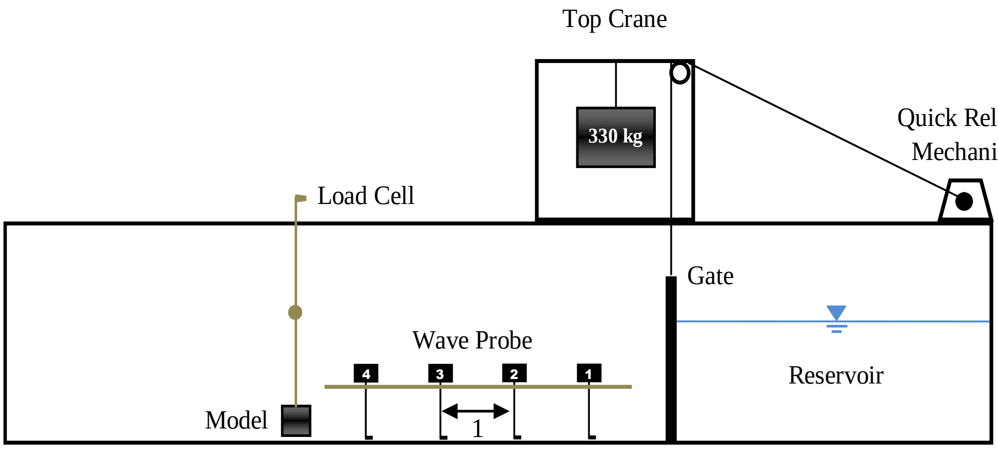
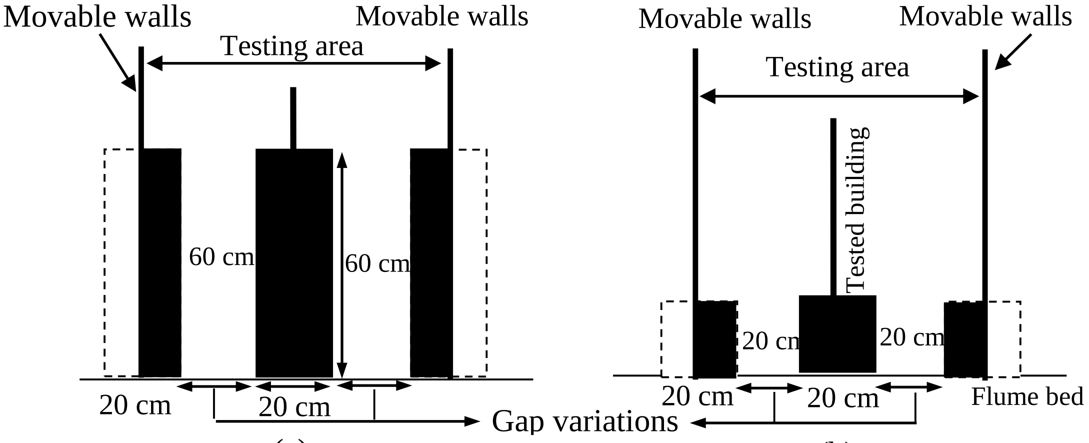


Figure 4. Experimental set-up

The model buildings were of square shape made of plywood. There were two types of models namely low buildings of 20 cm x 20 cm x 20 cm (width x length x height) in size and high buildings of 20 cm x 20 cm x 60 cm. The models were arranged in the flume either as single building (no nearby buildings) or as a row of buildings separated by gaps.

When simulating the force on row of buildings, the size of the buildings and the gaps were made uniform to simplify the model lay out. A model building was installed in the center of the flume on which tsunami force was measured. Two models of half width building size were installed at sidewalls representing the adjacent buildings. These sidewalls were made movable and parallel to the wall of the flume to represent mirrors or reflective boundary conditions (Figure 5). The distance between the sidewalls may be adjusted to suit the required gaps between the buildings. The lengths of the movable sidewalls were 2.4 m, of which the 1.4 m was upstream of the model buildings and the rest was downstream of the model buildings. The arrangement assured that the maximum force on the building was recorded before the backwater reached the upstream end of the sidewalls.



(a) (b)

Figure 5. Detail lay out of the model in the wave flume.

4. TSUNAMI SURGE PROFILES AND FRONT CELERITIES

Varying water depth in the basin varied the tsunami surge heights. These were 50 cm, 60 cm, and 70 cm. Typical results of the surge are provided in Figure 6. The arrivals of the surges at each station were used to calculate the surge speed as in Eq. (11).

$$U = \frac{\frac{x_{1-2}}{t_{1-2}} + \frac{x_{2-3}}{t_{2-3}} + \ldots \frac{x_{n-n+1}}{t_{n-n+1}}}{n_t}. \tag{11}$$

where $x_{n\text{-}n+1}$ is the distance between station n and station n+1, $t_{n\text{-}n+1}$ is the required duration for the surge to move from station n to station n+1, and n_t is the number of spaces between the probes in the wave flume.

Figure 6 indicates that the surge level fluctuated with time and along the flume. It may be said that the front depth (the average water depth of the front during the first one second of measurement) was the same between station 1, 2, and 3. At station 4, approximately 10 cm from the building model, the water depth significantly higher due to backwater. The tsunami surge speeds are shown in Table 1.

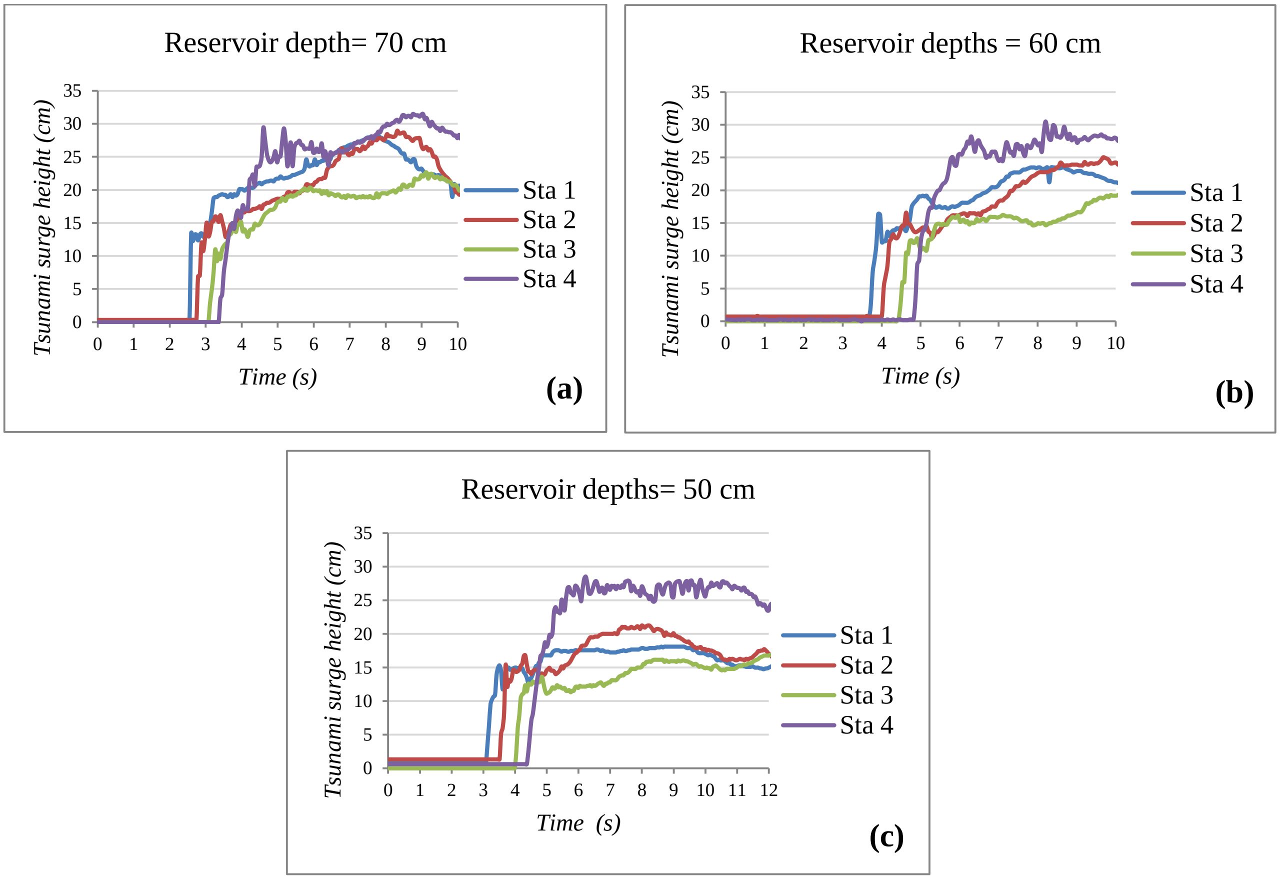


Figure 6. Tsunami surge profiles at station 1 (Sta 1) to station 4 (Sta 4) at different reservoir depths

Table 1. Tsunami surge characteristics

h_0	h_3	Average surge height (Experiment)	Average surge celerity (Experiment)	Calculated surge height based on Eq. (2)	Calculated surge celerity based on Eq. (2)	F_r
50 cm	2 cm	14.89 cm	2.40 m/s	14.32 cm	2.39 m/s	1.99
60 cm	2 cm	16.17 cm	2.76 m/s	16.09 cm	2.67 m/s	2.19
70 cm	2 cm	17.05 cm	3.08 m/s	17.75 cm	2.93 m/s	2.38

From Table 1, it may be said that the present experiment agrees well with the theoretical solution by Chanson's (2005). The range of Froude numbers in the present study was approximately from 2.0 to 2.4.

4 TSUNAMI FORCE ON SINGLE BUILDING

Tsunami force on buildings may be approximated using a number of equations as discussed previously. For low building, Eq. (5) may not be suitable, as the overflow water does not contribute to the force. For low buildings where the height of the buildings are almost the same as the height of the surge, Triatmadja and Nurhasanah found that C_f values were 0.69, 0.62, and 0.53 at F_r equals 2.13, 2.30, and 2.53 respectively. For high buildings C_f value was reported to be 1.03 at F_r= 2.13. Similarly the average F_r in the present study was 2.2 and hence the results of the present study are comparable to that of Triatmadja and Nurhasanah.

Eq. (4) may also be applicable where C_D equals 2.0 (Dean and Darlymple, 1984) or 1.25 for ratio between the inundation depth and the width of the building is 1 to 12 (FEMA, 2005). The experimental results are given in Figure 7 together with predicted forces based on Eq. (4), Eq. (5), and Eq. (6). It may be said that in general the existing formulae under predict the experimental data yet, the differences are not significant at low buildings. Eq. (5) tends to under predict the experimental data for higher F_r. This is because the dynamic force, which actually depends on surge velocity and depth, has been simplified by replacing U with h. However, U is related to both F_r and h, and hence replacing U with h implies a constant F_r. Therefore, when in reality F_r increases, Eq. (5) under predicts the force and vice versa.

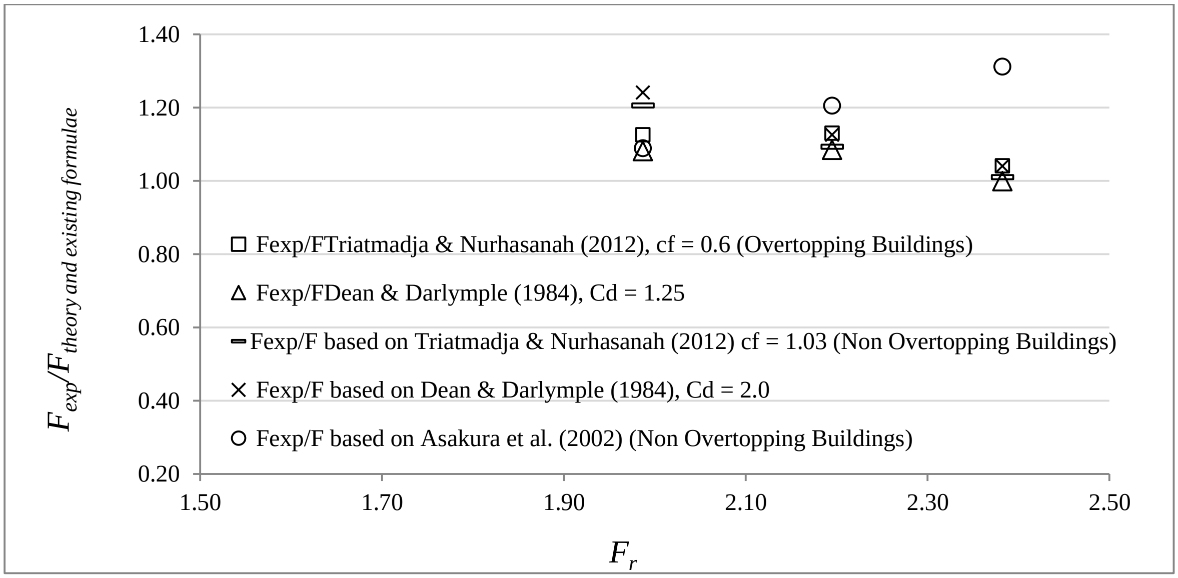


Figure 7. Experiment versus estimated surge force on low and high buildings.

5 TSUNAMI FORCE ON ROW OF LOW AND HIGH BUILDINGS

Rows of similar buildings (houses) with spaces or gaps in between are common in a newly designed residential complex as found in Aceh after reconstruction following the tsunami disaster in 2004. In this case, tsunami may penetrate the building complex through the gaps whilst at the same time the buildings reflect the waves to create backwater as discussed previously. Smaller gaps reduce more wave energy downstream and so the front buildings may be regarded as a protection to the downstream buildings. However, smaller gaps create higher backwater and higher force on the front buildings. The deceleration of surge flow through rows of buildings may be perceived as the deceleration of the surge through a large building with openings. The force of which is given in Eq. (7). The force per unit area (P) based on Eq. (7) may then be formulated as:

$$P = \frac{C_f(1-n^2)\rho BhU^2}{(1-n)Bh} = C_f(1+n)\rho U^2. \qquad (12)$$

Eq. (12) suggests that the average pressure on a building area alone (not including the openings) is higher than the average force on solid rectangular building of the same size.

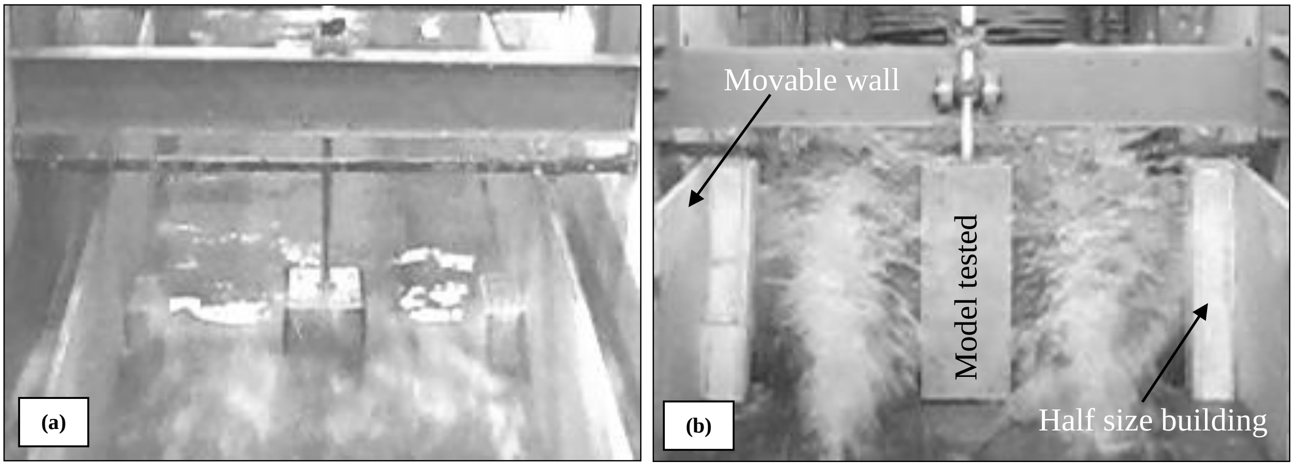


Figure 8. (a) Front view of row of low buildings and (b) Rear view of row of high buildings during the experiment

Low buildings may be overtopped easily and hence, the backwater upstream of the buildings is limited to certain height after which the sum of the flow over the buildings and through the gaps balances the tsunami surge flux. On the other hand, there is no flow over the high buildings that cause higher backwater. Hence the effect of the gap size becomes more significant.

Realizing the importance of certain variables namely gap width, projected area of the building, projected area of adjacent buildings, tsunami surge velocity, and density of the water, a dimensional analysis was performed to group such important variables into non dimensional parameters.

Figure 9 shows the results of the experiment and their relations with the non-dimensional parameters. Eq. (13) was determined based on non-dimensional parameters to fit the experimental data,

$$F = C_{fg}\rho U^2 (AA')^{0.535} G^{-0.14} \; ; \; 0.01 < AA'/G^4 < 3500 \qquad (13)$$

where A is the projected area hit by tsunami, $A' = B\,h'$ is the projected area of the adjacent building, B is the width of single building, h' is the height of the building, G is the gap between the buildings. The value of C_{fg} is 1.0 for $h/H < 1.33$ (low building) and 1.6 for $h/H > 1.34$ (high building). As can be observed in Figure 9, the equations fit quite well with the data for a large range of AA'/G^4.

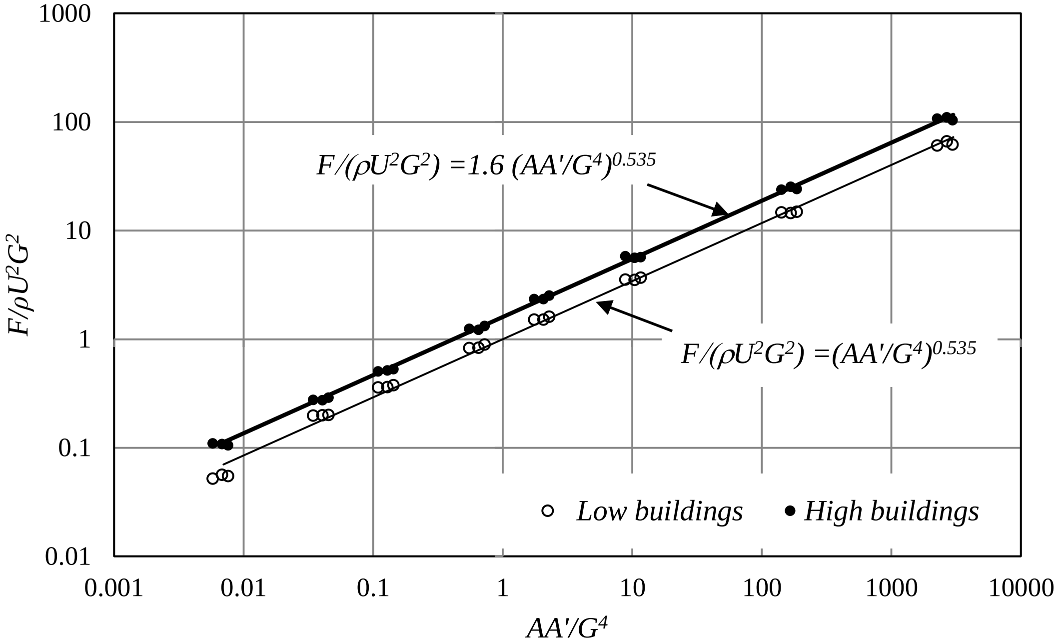


Figure 9. Relation between non-dimensional parameter AA'/G^4 and $F/\rho U^2G^2$

Eq. (13) was compared with the experimental data for low buildings and with other existing formulae in Figure 10. For large gaps the agreement was satisfactory at high F_r and approximately 20% less than the experiment at lower F_r. At small gaps Eq. (13) fit better for lower F_r, and approximately 15% higher than the experimental at larger F_r. Eq. (7) over predicts the experimental data by less than 10% except at large gaps where the discrepancy is nearly 30% for small F_r. The use of Asakura's et. Al equation (Eq. 5) directly on the problem is shown to be in appropriate. Eq. (5) was meant to be applied to single building without any disturbance from the surrounding. The inclusion of Eq. (5) in the figure is merely to provide comparison between tsunami forces on single building without any disturbance from the surrounding and those with the effect of the surrounding. As can be seen in the figure that as the gap becomes wider, the effect of the gap becomes less significant. Note that Eq. (5) fits better to the experimental data for F_r close to 2.0. As F_r increases, Eq. (5) under predicts the experimental data.

Similar comparison is given in Figure 11 for high building. In average the performance of Eq. (13) is similar to Eq. (7).

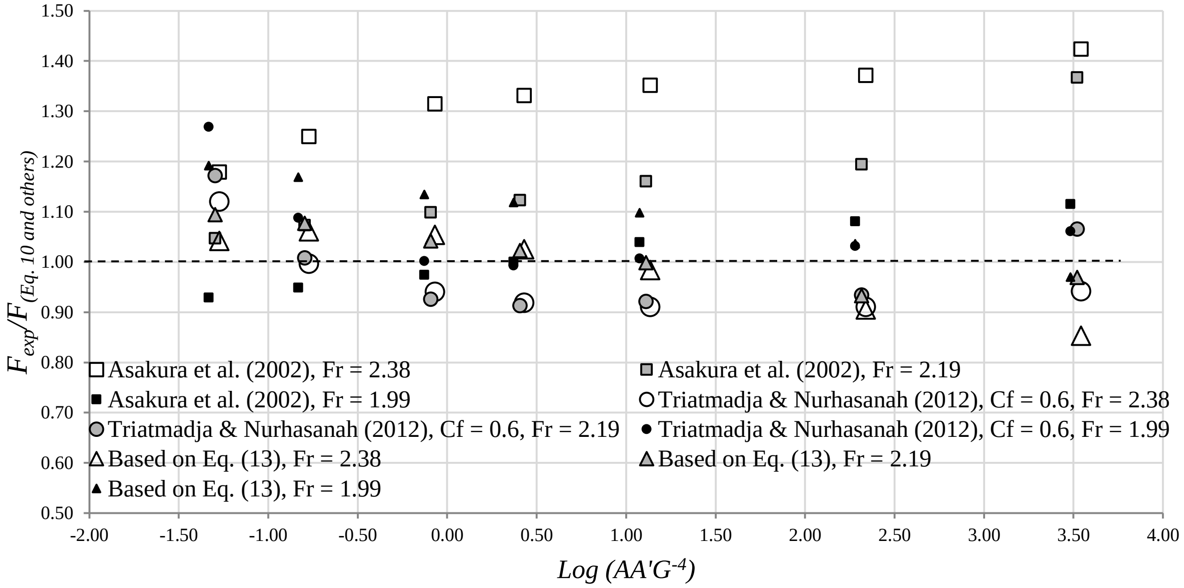


Figure 10. Comparison of Eq. (5), Eq. (7), and Eq. (13) with the experimental data on low building. Eq. (5) is compared only with tsunami force on high buildings. Higher F_r is indicated by larger symbol.

Figure 12 shows the increasing tsunami force on low buildings as a function of relative gap width. The increasing force is calculated as the ratio between the force with the effect of nearby building and the force of single building. It is noted that tsunami force may increase approximately up to more than 60% when $G/(B+G) = 0.46$. Example of such a row of buildings is depicted in Figure 2. In the future, the owner or the resident of these buildings may build additional rooms next to the main building for garages or sleeping rooms, which narrow down the space between the buildings. In this case, tsunami force on the building is expected to increase. Figure 12 indicates that for $G/(B+G) = 0.1$ the force on the building is approximately 85% higher. The percentage increase of force relative to reducing $G/(B+G)$ is higher for high buildings as tsunami surge may only flow through the gaps and hence the reduction of the gap is more effective in increasing the force. The experimental results indicated that the maximum increase is nearly 90% more than that of single building. The maximum increased of the force on single high building may be calculated using Eq. (10) and Eq. (5) or Eq. (6) based on the data. For F_r =1.99, the maximum increased was found to be 76% (using Eq. (5)) and 73% (using Eq. 6) which were relatively close to the experiment. For higher Froude number, the maximum increased force may be calculated using Eq. (10) and Eq. (6) to give 96% and 81% increased force for F_r = 3.08 and 2.6 respectively. These values are good approximation to the experimental data despite the assumption used in Eq. (10) where the speed and the height of the surge were constant whilst in reality the speed reduces with the increasing surge height behind the front (Lukkunaprasit et. al, 2009).

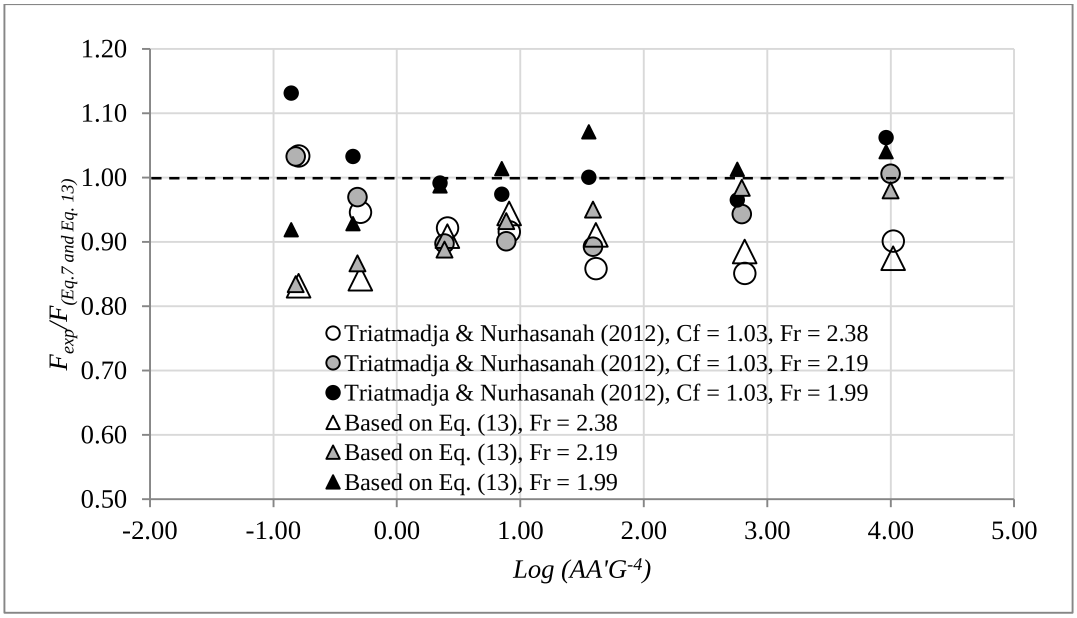


Figure 11. Comparison between Eq. (7), Eq. (13) and the experimental data on high building. Higher F_r is indicated by larger symbol.

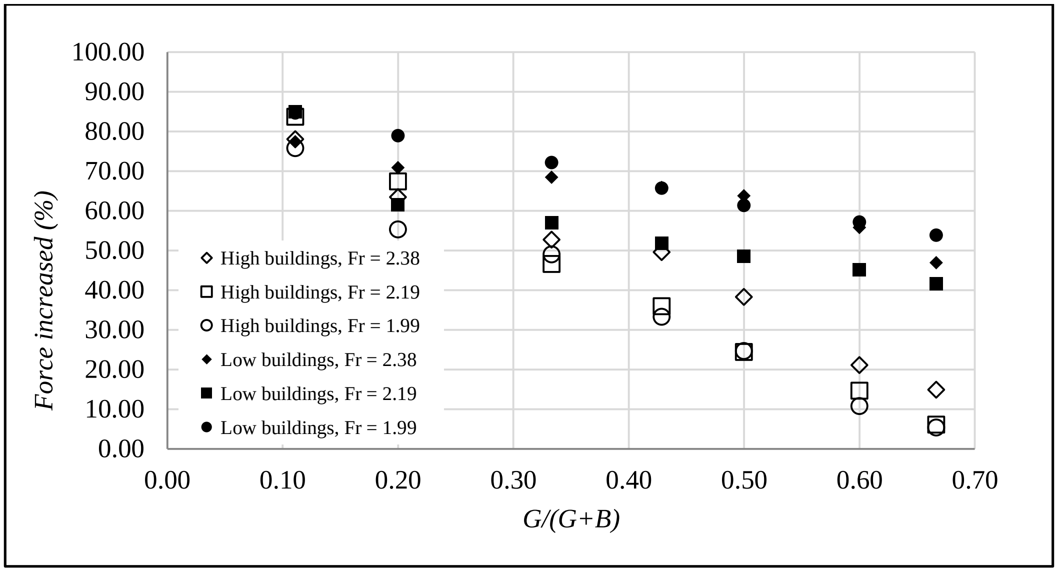


Figure 12. Relative increase of tsunami force on low and high buildings due to surrounding buildings

6 CONCLUSION

The tsunami force on buildings depends on the surrounding adjacent buildings. The gaps or space between buildings have a significant effect on the tsunami surge force. Such force may be calculated using Eq. (13). The maximum force on buildings where the tsunami surge is totally reflected can be approximated using Eq. (10). Houses in a residential complex such as those in Aceh should be designed by considering the effect of nearby buildings since even a relatively small tsunami may bring about large force that endangers the houses and hence the residents.

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REFERENCES

Asakura. R., Iwase. K., Ikeya. T., Takao. M., Kaneto. T., Fuji. N., Ohmori. M., (2002), The Tsunami Wave Force Acting on Land Strctures, Coastal Engineering.

Chanson. H.,(2005), *Hydraulic Model Reports Ch55/05*, University of Queensland.

Dean. R.G., and Dalrymple. R.A., (1984), *Water Wave Mechanics for Engineers and Scientists*, World Scientific Publishing, Singapore

FEMA P-55, (2005), Coastal Construction Manual, Volume II, Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Buildings in Coastal Areas, FEMA.

Lukkunaprasit. P., Ruangrassamee. A., and Thanasisathit. N., (2009), Tsunami Loadings On Buildings With Openings, *Science of Tsunami Hazards*, Vol. 28, No. 5, p 303-310.

Nakano.Y., (2010), Design Load Evaluation For Tsunami Shelters Based On Damage Observations After Indian Ocean Tsunami Disaster Due To The 2004 Sumatra Earthquake, Science of Tsunami Hazard, International Journal of the Tsunami Society, Vol. 29. No. 1, pp. 11-20.

Takahashi. M., Tanaka. S.,Kimura R., Umitsu. M., Tabuchi. R., Kuroda. T., Ando. M., Kimata. F., (2007), Restoration After The Sumatra Earthquake Tsunami In Banda Aceh: Based On The Results Of Interdisciplinary Researches By Nagoya University, *Journal of Natural Disaster Science*, Volume 29, Number 2, 2007, pp53-61

Triatmadja. R., and Nurhasanah. A., (2012), Tsunami Force on Buildings with Opening and Protection, *Journal of Earthquake and Tsunami*, vol. 6, No. 4 (2012).

US Army Engineer Waterways Experiment Station and Coastal Engineering Research Center (1990), Wave Forces on a Wall Shoreward of the Still-Water Line, *Coastal Engineering Technical Note*.