TSUNAMI FORCE ON LOW BUILDING AND THE EFFECT OF SURROUNDING BUILDINGS

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ABSTRACT: Today tsunami hazard has become an important aspect in national security of Indonesia and generated many researches. Tsunami disaster in the Hindian Ocean 2004 has caused a lot of buildings damaged and probably the greatest loss of lives ever due to tsunami. This research aims to analyze the tsunami force acting on the low building or overtopping building and the effect of other buildings nearby. The research was conducted using physical model at the Hydraulic and Hydrology Laboratory, Research Centre for Engineering Science, Gadjah Mada University Yogyakarta. The physical model simulations were carried out in the wave flume of 24 m long, 1.5 m high, and 1.45 m width that was facilitated with tsunami generator based on dam break system. The buildings were placed in a row perpendicular to tsunami wave flume. The distances between the buildings were varied to observe the effect of such opening on the impact. The physical simulation represented the tsunami attack in Aceh in 2004, where the houses and other low structures were overtopped by tsunami. The building models were made of plywood. Data acquisition was carried out using a load cell to measure the total force on the building. The results shows that the maximum force depends on the opening between the buildings and that higher building nearby gave more impact to the building investigated. Simple equations for practical use are proposed to calculate the tsunami force on the overtopping building with the effect of the surrounding buildings.

Keywords: Tsunami, overtopping, gap, force, dam break

INTRODUCTION

The phenomenon of the Indian Ocean Tsunami in 2004 with a huge wave reached the land has caused severe damage to infrastructure and loss of lives. Aceh suffered the greatest losses in this catastrophic. The incident has made Aceh realized that they are too vulnerable to the tsunami. After the tsunami on 26 December 2004, Aceh once again struck by tsunami in the area of Simeulue and Nias Islands on 26 March 2005. Another potential earthquake generated tsunami 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 the earthquake did not generate tsunami, it has made Acehnese became more alert and learned how to prepare against such horrible hazard.

After the 2004 tsunami in Aceh, many coastal forests that serve as buffer zones were completely rooted up. At present, the new residential areas, schools, hotels, and industrial areas after reconstruction are directly open to the sea. Coastal forest is an alternative measure for reducing tsunami naturally but it requires considerable time to grow to achieve the required strength to function properly. Proper arrangement of buildings in coastal areas may contribute to reducing the damage caused by tsunami. Such layout is for instance by providing a weaker building under the protections of stronger buildings that are designed properly. The weaker houses are for example the tsunami victim houses (Figure 1) that were built by government and Non-Government Organization (NGO). Unfortunately, at present arrangement, some of the houses would be the first to suffer tsunami surge force. When the weaker buildings are destroyed or lifted up by tsunami, they may be

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brought further inland, hit other buildings, create more damages and increase loss of lives. In this paper, the effect of layout of buildings, especially the distance between buildings or the size of the gap was studied.

LITERATURE REVIEW

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 may be described by Eq. (1).

\[
U = k \sqrt{gh}
\]  

(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 at a non-zero downstream depth is hardly affected by friction bed as suggested by Eq. (2) (Chanson, 2005).

\[
\sqrt{h_0} = \frac{1}{2} U \sqrt{\frac{1}{gh} (1 - \frac{1}{X}) + \sqrt{X}}
\]  

(2)

\[
X = \frac{1}{2} \left( \frac{1 + 8 \frac{U^2}{gh} - 1}{\sqrt{1 + 8 \frac{U^2}{gh}}} \right)
\]  

(3)

where \( h_0 \) is the initial of downstream water depth, with \( h_0/h_3 = X \), and \( h \) is the surge height or depth.

Triatmadja and Nurhasanah (2012) indicated that obstacles such as buildings may hinder tsunami flows and create backwater or higher water depth upstream of the obstacles resulting in higher tsunami surge speed along the gaps between the obstacles. In such situation, it may be expected that the obstacles them shelves are subject to higher tsunami forces. The force on single building may be calculated based on many available formulae. 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 chapter.

Tsunami Force on a Vertical Wall

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

\[
F_i = C_i \rho AU^2
\]  

(4)

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. (5) (Dean and Dalrymple, 1984).

\[
F_d = \frac{1}{2} C_D \rho AU^2
\]  

(5)

where \( C_D \) is the drag coefficient, \( A \) is the projected area, and in this case, \( U \) is tsunami celerity. 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.

Triatmadja and Nurhasanah (2012) suggested the use of Eq. (4) with \( C_i \) as the combination of both impact and drag forces as in Eq. (6).

\[
F = C_f \rho AU^2
\]  

(6)

where \( C_f \) was shown to be 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:

\[
F = C_f \rho (1 - n^2) BhU^2
\]  

(7)

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

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 reservoir for generating tsunami whilst the downstream part was used to simulate tsunami propagation and tsunami force on buildings. The gate that separates the flume was equipped with 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 physical model used by Triatmadja and Nurhasanah (2012).

With the above arrangement of reservoir and quick gate opening system, a dam break surge may be generated to imitate tsunami surge. This was carried out by opening the gate vertically. In order to measure the surge front celerity, a series of wave recorders were installed at selected stations (Sta). There were 4 probes used to measure surge height and installed in front of model along the flume. The distance between the adjacent stations, from Sta 1 to Sta 4, was 1 m, as depicted in Fig. 2.
The model buildings used in the research were of square shape made of plywood. There was one type of models namely low buildings of (width x length x height) 20 cm x 20 cm x 20 cm in size. 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 buildings in rows with gaps in between, the size of the buildings and the gaps were assumed uniform, hence the model layout can be simplified. 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 side walls as the adjacent buildings. These side walls were made movable and parallel to the wall of the flume to represent mirrors or reflective boundary conditions (Fig. 2). The arrangement of the models was parallel to the wall of the flume to represent mirrors or reflective boundary conditions. The arrangement assured that the maximum force on the building was recorded before the backwater reached the upstream end of the side walls. The detail of model set-up in the laboratory is showed in Figure 3 below.

The tsunami surge heights were varied by varying water depth in the basin. These were 50 cm, 60 cm, and 70 cm. Typical results of the surge are provided in Fig. 4. The arrivals of the surge at each station were used to calculate the surge speed as in Eq. (8).

$$U = \frac{x_{n+1} - x_n}{t_{n+1} - t_n}$$  \hspace{1cm} (8)

where $x_{n,n+1}$ is the distance between station $n$ and station $n+1$, $t_{n,n+1}$ is the time of wave propagation between station $n$ and station $n+1$, and $n$ is the number of spaces between the probes in the wave flume.

Fig. 4 Tsunami surge profiles at station 1 to station 4 with different reservoir depth.

Fig. 4 indicates that the surge level fluctuated along the flume with time. It may be said that the front depth (the average water depth of the front during the first one second of measurement) were 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.
Table 1. Tsunami surge based on present experiment and analytical solution of Chanson (2005).

<table>
<thead>
<tr>
<th>( h_0 )</th>
<th>( h_1 )</th>
<th>( H )</th>
<th>( U )</th>
<th>( H )</th>
<th>( U )</th>
<th>( F_r )</th>
</tr>
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<tbody>
<tr>
<td>cm</td>
<td>cm</td>
<td>Exp</td>
<td>Exp</td>
<td>Eq. (2)</td>
<td>Eq. (2)</td>
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<td>2</td>
<td>14.89</td>
<td>2.40</td>
<td>14.32</td>
<td>2.39</td>
<td>1.99</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>16.17</td>
<td>2.76</td>
<td>16.09</td>
<td>2.67</td>
<td>2.19</td>
</tr>
<tr>
<td>70</td>
<td>2</td>
<td>17.05</td>
<td>3.08</td>
<td>17.75</td>
<td>2.93</td>
<td>2.38</td>
</tr>
</tbody>
</table>

From the table, it may be said that Chanson’s (2005) solution agrees well with the present experiment. The range of Froude numbers in the present study was 2.0 to 2.4.

TSUNAMI FORCE ON SINGLE BUILDING

Tsunami force on a building is influenced by the area could be reached of surge. So though it has a high of surge inundation, the total force on the inland building only occur in the affected area of the building where the surge height impacted the building and vice versa.

Tsunami force on buildings may be approximated using a number of equations as discussed previously. For low buildings where the height of the building 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. The average \( F_r \) in the present study was 2.2 which was slightly lower than that used by Triatmadja and Nurhasanah and hence the result of the present study may be directly comparable to that of Triatmadja and Nurhasanah.

Eq. (5) may also be applicable where \( C_D \) equals 1.25 for ratio between the inundation depth to the width of the building is 1 to 12 (FEMA, 2005). The experimental results are given in Fig. 5 together with predicted forces based on 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.

![Fig. 5 Observed result versus estimated wave force by other formulae for low buildings.](image)

EFFECT LOW OF ADJACENT BUILDINGS

Rows of similar buildings (houses) with space or gaps in between are common in a newly designed residential complex as also happen in Aceh after reconstruction following the tsunami disaster in 2004. In this case, tsunami waves may penetrate the building complex through the gaps whilst at the same time the buildings reflect the waves to create back water. The gaps play important role in reducing the flow and consequently cause back water. Smaller gaps reduce more wave energy downstream and so the front buildings may be regarded as protection to the downstream buildings. However, smaller gaps create higher backwater which subsequently add to the drag force on the front buildings.

![Model tested, front view of row of low buildings during the experiment](image)

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.

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.

Fig. 7 shows the results of the experiment and their relations with the non dimensional parameters. Eq. (9) was determined based on non dimensional parameters to fit the experimental data.

\[
F = 1.05 \rho U^2 (AA')^{0.54} G^{0.116}
\]  

(9)

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, \( h' \) equals 20 cm, and \( G \) is the gap between the buildings. As can be observed in Fig. 7, the equations fit reasonably well with the data even for large \( AA'/G^2 \) which represents very narrow gap. Fig. 7(B) and Fig. 7(C) show the detail of the data fitting with Eq. (9) at lower \( AA'/G^2 \) or at wider gaps. Fig. 7(C) especially shows the agreement of the equation even at \( AA'/G^2 \) close to zero representing very wide gaps.
CONCLUSION

Tsunami force on buildings depends on the surrounding such as the adjacent buildings. The gaps or space between buildings have significant effect on the contribution of force. Such force may be calculated using Eq. (9). The application of the equation to low built of residential complex showed that tsunami forces should be considered, as even relatively small tsunami may bring about large force that endanger the buildings.

Fig. 8 Comparison of Eq. (7) and Eq. (9) with the experimental data. Higher $F_s$ is indicated by larger symbol.

Fig. 9 shows the increasing force due to tsunami blockage of low buildings where compare the force result of single building ($F_s$) and group buildings ($F_g$). It is noted that tsunami force may increase approximately more than 30% when the width of the gap between low buildings is similar of the building size (or $G/(B+G) = 0.50$). Example of such building row is depicted in Fig. 1. In the future, the resident of the buildings may construct additional room next to the main building for garage or a sleeping room which narrow down the space between the buildings. In this case, tsunami force on the building is expected to increase. Fig. 9 indicates that for $G/(B+G) = 0.06$ (narrow gap) the force on the building is approximately 46% higher with different $F_s$.

Fig. 9 Increasing force effect of multiple buildings
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