PHYSICAL EXPERIMENTS OF TSUNAMI RUN-UP AND FORCE ON BUILDING CLUSTER USING A HYBRID TSUNAMI GENERATOR

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ABSTRACT

A series of experiments was conducted to investigate tsunami run-up and force on structures using a cutting-edge tsunami wave generator, the Hybrid Tsunami Open Flume in Ujigawa Laboratory (HyTOFU). The experiments were performed using both single and multiple structures configurations that represented buildings with 1:20 length scale. The effects of distance, number of structures, and spacing between elements were examined to estimate forces acting on the structures with seven different generated waveforms. Tsunami run-up and force have been demonstrated clearly through these experiments. In the single structure cases, water surface elevation and pressure were influenced significantly by the distance between specimen and coastline. In the multiple structure cases, the effect of macro roughness elements around the specimen varied based on the number of structures and the spacing distance between elements. Generally wider spacing can contribute higher impact on the structures.

KEYWORDS: Hybrid tsunami flume, tsunami generator, run-up, tsunami force, physical experiment

1 INTRODUCTION

The 2011 Tohoku Earthquake Tsunami induced severe destruction on buildings and other man-made structures up to several kilometers from the coastline. Even in Japan, a country with a good reputation for preparedness and mitigation against tsunami disasters, the countermeasure structures failed to protect coastal cities during the 2011 event (Mori et al., 2013). The coastal defense structures along the northeastern coast experienced failure and were unable to protect infrastructures behind. Some reinforced concrete buildings were totally destroyed and inundation area exceeded predictions (Mase et al., 2011; Supasri et al., 2013).

Understanding tsunami hydrodynamics such as run-up and force is an essential aspect in the development of tsunami resilient structures. Recently, many researchers have investigated tsunami run-up and force using both numerical and physical modeling (Fujima et al., 2009; Bridges et al., 2010; Rossetto et al., 2011; Palermo et al., 2012; Goseberg et al., 2013; Park et al., 2013; and Thomas et al., 2014). However, most of them used a conventional and simple waveform that idealized the tsunami waveform in hydraulic experiments.

The 2011 Tohoku tsunami had different characteristics and shape than previous events. Hayashi et al., (2011), and Kawai et al., (2013) showed the transformation of the 2011 Tohoku tsunami began with an initial impulsive wave, increased gradually with small and slow waves, then the water surface elevation rose dramatically and quickly reached the peak of highest crest. Crest height gradually decreased and was followed by a wave train with high constant height and long period. Hence, the option to use a simple wave such as a solitary, N-shape, or long-sinusoidal wave to represent a tsunami wave was categorized as outdated (Madsen et al., 2008).

To reproduce the 2011 Tohoku Earthquake-like tsunami with higher detail and accuracy, including a steep wave with very long current, a new mechanism of tsunami generation in physical modeling is needed. The Disaster Prevention Research Institute Kyoto University, built a new tsunami wave generator in 2014: the Hybrid Tsunami Open Flume in Ujigawa Laboratory (HyTOFU). HyTOFU is a cutting-edge laboratory-based wave model designed to model tsunami wave generation and is equipped with three types of wave makers: mechanical piston-type wave generator, head storage tank-driven wave generator, and pump-driven wave generator. These three mechanisms can not only be used individually but can be used concurrently in any combination of the above three types (Prasetyo et al., in press).
In this study, we used the HyTOFU to investigate tsunami hydrodynamic processes such as tsunami run-up and force on single and multiple structures and to understand the interaction of macro-roughness effects on tsunami wave transformation.

1.1. Experimental setup

A series of experiments was conducted to investigate tsunami run-up and force on structures using HyTOFU. The HyTOFU basin is 45 m long, 4 m wide, and 2 m deep with bathymetry consisting of a flat bed with smooth cement mortar running 14.05 meters from the paddle piston to a 1:10 slope bed of length 7.95 m and ending with a flatbed made of metal. This flat bed is an idealized land condition where instrumented box experiments were located and which was assumed to be without friction. The initial water depth is 0.7 m and can be adjusted as needed. Schematics of the experimental setup are illustrate in Figure 1 (a).

The HyTOFU is capable of generating a solitary wave up to 1.0 meter height by a piston-paddle with a 2.5 m stroke. This flume also can produce a constant and periodical wave with maximum discharge about 0.83 m$^3$/s generated by pump with two outlets of size 2 m x 0.2 m. The last mechanism to generate the wave is by dropping a volume of water from an overhead storage tank into the flume by opening its gate like a dam break mechanism. However, this mechanism was not used in this study. Figure 1 (b) shows layout of HyTOFU.

![Figure 1. (a) Schematic view of HyTOFU. Wave gauges (WG) and Acoustic Doppler Velocimeter (ADV) are represented by green rectangular and blue circles, respectively, (b) Layout of HyTOFU was equipped by three type of wave generation, and (c) Specimen of box experiment instrumented by pressure sensor, wave gauges and ADV were located in front and lateral side of specimen](image-url)
In these experiments, the model scale was 1:20. We used an instrumented box or specimen to represent an 8 m long x 8 m wide Japanese house. The specimen was made of acrylic with dimensions 0.40 m long x 0.40 m wide x 0.50 m high and was equipped by pressure sensors on each side. The other boxes were the same size but were made from iron plate to represent macro-roughness structures. Nine pressure sensors with capacity 50 kPa were installed on the front side, in addition to seven sensors on lateral and seven sensor on rear sides of specimen. Sensors were placed at elevations \( z = 0.01 \) m, \( z = 0.05 \) m, and \( z = 0.15 \) m height on the specimen. Figure 1 (c) shows a photograph of the specimen condition with pressure sensors installed on its side.

Water surface elevations were measured using wire resistance wave gauges (WGs) along the flume (Figure 1 (a)). One WG was located offshore at \( x = 9.5 \) m, four WGs were located on the slope at \( x = 14.5 \) m, 16.5 m, 18.5 m, and 20.5 m from the piston-paddle, respectively, and various WGs were located onshore depending on the experimental configuration. The WGs measured time series of water surface elevation \( (\eta) \) above the design water depth including the incident, run-up and reflected wave. To measure flow velocity, we used Acoustic Doppler Velocimeters (ADV, Nortec Vectrino). One ADV was located offshore at the same location as WG3 and three ADVs were located around the boxes configuration. In this paper, velocity measurements are not presented but will be used for further investigation in the future analyses.

1.2. Experimental procedure

To investigate characteristics of tsunami run-up and tsunami force, seven combinations of wave generation were determined. We set up the experiment with various combinations of solitary wave and constant flow inputs. The first experiment was conducted by generating constant flow only (solitary wave input, \( \eta = 0 \), pump discharge, \( Q = 0.8 \) m\(^3\)/s). Subsequently, the solitary wave input was increased while the constant flow input was decreased. Initial water depth \( (h) \) was set at 0.7 m. Experimental conditions can be seen in Table 1.

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Solitary wave input by piston-type, ( \eta ) (m)</th>
<th>Constant flow by pump, ( Q ) (m(^3)/s)</th>
<th>Water depth ( h ), (m)</th>
<th>( \eta/h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 m00p80</td>
<td>0.00</td>
<td>0.8</td>
<td>0.7</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 2 m10p60</td>
<td>0.10</td>
<td>0.6</td>
<td>0.7</td>
<td>0.14</td>
</tr>
<tr>
<td>Case 3 m15p40</td>
<td>0.15</td>
<td>0.4</td>
<td>0.7</td>
<td>0.21</td>
</tr>
<tr>
<td>Case 4 m20p30</td>
<td>0.20</td>
<td>0.3</td>
<td>0.7</td>
<td>0.29</td>
</tr>
<tr>
<td>Case 5 m25p20</td>
<td>0.25</td>
<td>0.2</td>
<td>0.7</td>
<td>0.36</td>
</tr>
<tr>
<td>Case 6 m35p10</td>
<td>0.35</td>
<td>0.1</td>
<td>0.7</td>
<td>0.50</td>
</tr>
<tr>
<td>Case 7 m40p10</td>
<td>0.40</td>
<td>0.1</td>
<td>0.7</td>
<td>0.57</td>
</tr>
</tbody>
</table>

In this study, we conducted an experiment for two conditions:

Condition 1: single box experiment. The goal of this experiment was to observe characteristics of tsunami wave run-up and force on a single structure corresponding to different locations from the coast line. The specimen was placed in the flume at three different locations: 0.79 m \( (L_1) \), 1.59 m \( (L_2) \) and 2.39 m \( (L_3) \), respectively. Then, various tsunami waves were generated. Measurement of tsunami run-up and force used wave gauges and pressure sensors installed on the front, lateral, and rear sides of the specimen.

Condition 2: multiple box experiment. The goal of this experiment was to investigate tsunami behaviour and effects of macro-roughness elements relative to the specimen. Two different setups of macro-roughness were arranged by varying the number of boxes and spacing between boxes. We set a gap spacing between the box experiments representing a street around the houses with two conditions: \( a_1 = 0.2 \) m and \( a_2 = 0.4 \) m. The specimen was located at \( x = 23.39 \) m from the piston-paddle for the gap spacing \( a_1 = 0.2 \) m, and \( x = 23.59 \) m for \( a_2 = 0.4 \) m. In the first experiment, we used three boxes (including specimen) where the first box was placed in front of specimen and a second box was placed behind the specimen. For the second experiment, we used nine boxes in a 3 x 3 array and put the specimen in the middle of box configuration. The configurations of single and multiple box experiments can be seen in Figure 2. The variable of \( f_i \) means we installed wave gauges and ADVs to measure the wave height \( (\eta) \) and flow velocity \( (u) \) in front of the specimen. \( i \) means we installed wave gauges and ADV in lateral side and \( r_i \) means we install wave gauge and ADV in rear side where \( i = 1 \) (for \( L_1 = 0.79 \) m), \( i = 2 \) (for \( L_2 = 1.59 \) m), \( i = 3 \) (for \( L_3 = 2.39 \) m). In the multiple boxes experiments, \( i = 1 \) (for spacing between boxes, \( a_1 = 0.2 \) m), \( i = 2 \) (for spacing between element, \( a_2 = 0.4 \) m).

To analyse the relationship between the tsunami wave height and macro-roughness configuration, we examined the time series of wave profile for single and multiple box experiment at the offshore wave gauge (WG1). Figure 3 shows an example time series of wave profile in Case 3 and Case 7, respectively.
Figure 2. Layout of single and multiple box experiments: (a) 1_box experiments, (b) 3_box experiments, and (c) 9_box experiments

Figure 3. An example time series of wave profile in (a) Case 3, and (b) Case 7 for single and multiple box experiments. A symmetric solitary were formed at offshore wave gauge

2 EXPERIMENTAL RESULTS

Figure 4 shows an example of time series of tsunami wave height for Case 7 (input maximum solitary wave 0.4 m and constant flow 0.1 m$^3$/s) with various configurations, showing the wave height measured on the front side of specimen (WG9). The wave began to propagate from offshore to inland with a symmetric waveform as shown in Figure 3. An asymmetric waveform occurred when a tsunami wave propagate over the slope. In this figure, the oncoming tsunami wave as incident wave can be seen clearly and a small rise in water height occurred as a reflected wave, then followed by a constant flow. A reflected wave developed for all configurations except the zero box experiment. Comparison of wave height in the multiple box experiment indicates that water level for 0.4 m gap spacing was larger than that for the configuration with 0.2 m spacing. For example, maximum wave height at $f_{i2}$ increased by 128.2% compared with $f_{i1}$ (for 3_box experiments) and was increased 28.3% (for 9_box experiments). In this figure, we can also see the splash water that occurred on the front side of specimen for the single box experiment.
Figure 4. Examples of wave profile at front side of specimen in Case 7 for single and multiple box experiments

Figure 5 shows an example time series of maximum pressure at the front side of specimen for Case 7. P1 (black line) indicated the maximum pressure recorded at position $z = 0.05$ from the bottom, P2 (red line) at $z = 0.10$ and P3 (blue line) at $z = 0.15$. Impulsive wave force occurred when the tsunami wave hit the specimen and obtained maximum pressure. Thereafter, decreasing of water level due to the wave receding seaward led to a decrease in maximum pressure. When the reflected wave occurred and produced the second rise, pressure also increased gradually as a run-up force. Then, constant flow as quasi-static flow condition led to a constant pressure on the specimen resulting in a quasi-hydrodynamic force. These pressure pattern agree well with the experiments were conducted by Palermo, et al (2013).

Figure 5. Examples of times series of maximum pressure at the front side of specimen: P1 at position $z = 0.05$, P2 at $z = 0.10$, and P3 at $z = 0.15$

Figure 6 (a) shows incident wave height ($\eta_i$) as a function of solitary wave input ($\eta/h$) for each cases with different box configuration. The incident wave and reflected wave were normalized by initial water depth ($h$). The incident wave height tends to become large when solitary wave input increase from Case 1 ($\eta/h = 0$) to Case 7 ($\eta/h = 0.57$). There are several peak of incident wave height due to splash water. For example in Case 6 ($\eta/h = 0.5$) with 3_box 0.2m configuration have a highest value of incident wave height. Table 2 shows maximum incident wave height for all cases that measured in WG9. The bold value indicates that wave gauges measurement in the experiment recorded a splash water. Figure 6 (b) shows reflected wave height ($\eta_r$) as a function of solitary wave input ($\eta/h$). It was confirmed that constant flow generation did not produce the reflected wave as shown in Case 1 (solitary wave input = 0, constant flow = 0.8 m$^3$/s). For all configurations, the reflected waves were less than the incident wave height.

Figure 6 (b) shows reflected wave height ($\eta_r$) as a function of solitary wave input ($\eta/h$). It was confirmed that constant flow generation did not produce the reflected wave as shown in Case 1 (solitary wave input = 0, constant flow = 0.8 m$^3$/s). For all configurations, the reflected waves were less than the incident wave height.
Figure 6. (a) Incident wave height, and (b) reflected wave height as a function of solitary wave input

Table 2. Maximum incident wave height at WG 9 (in cm)

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 box</td>
<td>22.26</td>
<td>36.14</td>
<td>42.44</td>
<td>44.79</td>
<td><strong>48.26</strong></td>
<td><strong>48.69</strong></td>
<td><strong>49.33</strong></td>
</tr>
<tr>
<td>3_box0.2m</td>
<td>12.64</td>
<td>14.70</td>
<td>18.82</td>
<td>26.36</td>
<td>20.91</td>
<td><strong>80.26</strong></td>
<td>16.13</td>
</tr>
<tr>
<td>3_box0.4m</td>
<td>13.99</td>
<td>19.29</td>
<td>32.54</td>
<td><strong>53.14</strong></td>
<td><strong>43.60</strong></td>
<td><strong>52.68</strong></td>
<td>36.80</td>
</tr>
<tr>
<td>9_box0.2m</td>
<td>13.83</td>
<td>20.42</td>
<td>19.05</td>
<td>22.65</td>
<td>24.82</td>
<td><strong>35.27</strong></td>
<td>31.39</td>
</tr>
<tr>
<td>9_box0.4m</td>
<td>16.71</td>
<td>20.27</td>
<td>29.23</td>
<td><strong>50.85</strong></td>
<td>42.94</td>
<td>42.64</td>
<td>43.79</td>
</tr>
</tbody>
</table>

Figures 7 shows relationship between solitary wave input ($\eta/h$) and the maximum hydrostatic pressure ($\rho g h$) for each setback distance ($L_1 = 0.79$ m, $L_2 = 1.59$ m and $L_3 = 2.39$ m). Increasing the incident solitary wave height from Case 1 ($\eta/h = 0$) to Case 3 ($\eta/h = 0.21$) shows 1:1 agreement between the maximum pressure (at front side of specimen) and offshore hydrostatic pressure. However, the ratio of maximum pressure to hydrostatic force for Case 4 to Case 7 changes and becomes larger. The configuration with the specimen located closest to coastline ($L_1$) received the highest pressure compared to $L_2$ and $L_3$, except in Case 4. Therefore, setback distance from the coastline gives a significant impact on the specimen.

Figure 7. Relationship between solitary wave input and the maximum hydrostatic force

Figures 8 shows the relationship between solitary wave input and maximum incident wave height at front, lateral, and rear sides of specimen. The incident wave at all sides of the specimen have a similar heights for experimental Case 1 ($\eta/h = 0$), 2 ($\eta/h = 0.14$), and 3 ($\eta/h = 0.21$). However, starting at Case 4 ($\eta/h = 0.29$) the wave height began changing and water level at rear side had a smaller height than the front and lateral sides. The incident wave height tended to decrease for all cases with higher solitary wave. As the input solitary wave increased, the incident wave tended to decrease. Compared to
the water level on front side, the water level on the lateral side was lower by 30.2% and the water level on the rear side was lower by 53.2%.

![Graph showing relationship between solitary wave input and incident wave height at front, lateral and rear side of specimen](image1)

**Figure 8. Relationship between solitary wave input and incident wave height at front, lateral and rear side of specimen**

Figure 9 shows a comparison of hydrostatic force acting on structures between single and multiple box experiment at (a) front side, (b) lateral side, and (c) rear side of the specimen for all experiments. The ratio of maximum pressure to hydrostatic force on front side of specimen tends to increase linearly with the increasing solitary wave input. However, it decreases for the lateral and rear sides. Varying the number of surrounding boxes can give different impact to the specimen. For example, the specimen without any obstacles (1_box experiment) had highest maximum pressure on front and lateral side compared with the 3_box and 9_box experiments, but lowest maximum pressure on the rear side. Comparison of maximum pressure between the 3_box and 9_box cases showed different results for each side of the specimen. On front and lateral sides, maximum pressure for the 9_box experiment was higher than the 3_box experiment. Maximum pressure at rear side shows varying results. However, the 9_box case with spacing of 0.4 m shows higher impact than with spacing of 0.2 m. Based on experimental results as shown in Figure 9, wave height induced maximum pressure at the front, lateral and rear side of specimen with a nearly linear relationship. For example in the 1_box experiment case, $R^2$ at front side is 0.84, at lateral side = 0.41 and at rear side = 0.85

![Graph showing comparison of hydrostatic force acting on structures between single and multiple box experiments at (a) front side, (b) lateral side, and (c) rear side of the specimen](image2)

**Figure 9. Comparison of hydrostatic force acting on structures between single and multiple box experiments at (a) front side, (b) lateral side, and (c) rear side of the specimen**

The gap spacing between elements also can contribute different effects to the specimen. In experiments using 3_box and 9_box with spacing of 0.2 m, the impact tends to be smaller than in 0.4 m spacing. It can be concluded that wider spacing gave larger pressures than narrower spacing. However, note that decreasing the spacing can increase the water velocity and inundation height due to reflection from the other structures.
3 CONCLUSIONS

A series of tsunami physical modeling was conducted to examine tsunami run-up and force on single and multiple structures. The tsunami waves were generated by HyTOFU with combination of piston-type and pump driven wave generator. This study clearly showed that varying the number of structures and the spacing between them can significantly influence both inundation and force to the structure. If a single structure faces a tsunami wave directly without any obstacle, the distance between the structure and the coastline can give a significant impact to the maximum pressure felt by the structure. Single structures also can receive larger pressures from tsunami waves compared to configurations with multiple structures. Therefore shielding a specimen can reduce the tsunami impact. Effects of macro-roughness element to the specimen itself depend on gap spacing between elements. Wider spacing between elements can contribute higher pressure to the structure.

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