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Experimental Investigation on the Influence of Arrangement of Buildings on Tsunami Run-Up Flow

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Abstract: Physical experiments were conducted to clarify the change in tsunami flow patterns that can take place due to a variety of arrangements of coastal buildings, measuring the flow velocity, inundation depth and momentum flux around such structures. As a result, the shape of bow waves and wake waves around the buildings were found to change significantly depending on their arrangement. Changes in the shape of the bow wave and wake wave greatly affected the time series of inundation depth and velocity. As a result, the momentum flux varied between 30 and 140%, depending on the arrangement the buildings.

Keywords: Tsunami run-up, Tsunami design, Flow-structure interaction, Laboratory experiment, Tsunami wave force

1 Introduction

The 2011 Tohoku Earthquake and Tsunami caused massive damage to many coastal areas of the northern Tohoku region of Japan. Tsunami heights exceeded the heights of coastal defense at many places, and many structures were destroyed due to powerful waves, highlighting the necessity of improving tsunami countermeasures (Mikami et al., 2012, Jayaratne et al., 2016). However, reinforced concrete buildings, located near the shoreline, were also reported to have reduced the damage caused by the tsunami to other buildings further inland (essentially acting as shields). For instance, Kakinuma et al. (2012) conducted a tsunami trace survey in the northern part of Miyagi Prefecture, and reported that a group of reinforced concrete buildings, located in Onagawa Town, Miyagi Prefecture provided such a shielding effect. Hence, tsunami flows can be significantly influenced by the presence of sturdy structures, reducing damage to areas situated further inland. Thus, it is important for disaster risk managers to understand the effects of the different arrangement of sturdy buildings on the change in characteristics of tsunami flow, which can be utilized to formulate a range of mitigation strategies.

Following the 2011 event a number of researchers have studied the interactions between tsunami flow and coastal buildings, based on either hydraulic experiments or numerical simulations. For instance, Cox et al. (2008) conducted an experiment that showed that the speed of tsunami run-up was reduced by approximately 40% when several sturdy buildings were present in the coastal area (see also Rueben et al., 2011). Thomas et al. (2015) measured the tsunami force acting on a specimen which was placed behind multiple obstacles, and showed that the presence of obstacles could substantially decrease or increase the tsunami force, compared to the case when no buildings were placed in front of it. According to the experiments of Tomiczek et al. (2016), when there were one or two rows of obstacles in front of the specimen tsunami forces were reduced by around 40-70% due to the shielding effect (under breaking conditions). Goseberg and Schlurmann (2014) conducted physical experiments to measure the change in flow velocity around a single building or two buildings, which were placed parallel to a shoreline. By using a Particle Image Velocimetry (PIV) they were able to describe the process of development of the wake angle behind them.

However, to the authors’ knowledge there had been no studies that have investigated the effects of different arrangements of buildings on tsunami flow. Thus, in the present study the authors conducted
hydraulic experiments to clarify how flow direction, flow depth, and flow velocity in the vicinity of coastal buildings can be altered according to building arrangement.

2 Laboratory experiment

In the present study, a total of 9 building layouts were investigated. For this, two different types of instrumental configurations were employed, with the first one measuring inundation depths around the buildings, and the second one the spatial distribution of velocity with respect to time. For the first configuration type capacitive wave gauges were used, while the second employed experiment Particle Image Velocimetry (PIV) equipment. The experiments were conducted at a 1:60 scale.

2.1 Tsunami Wave Basin

Hydraulic experiments were conducted at the tsunami wave basin of Waseda University (dimensions 4 m wide, 9 m long and 0.5 high), in Tokyo, Japan (Fig. 1). A tsunami generator is located at one end of the basin. It is possible to store water inside this generator, and by opening the air-valves on its top the stored water can be released, generating a tsunami-like flow. Detailed information about this generator can be found in Nistor et al. (2016). In the present study, the authors started each experiment by storing water inside the generator to a height of 60 cm.

In order to investigate the flow in the vicinity of the target “buildings”, an area 0.8 m in length and 0.7 m in width was set as the target area for the PIV analysis (with all building models being placed in this area). To increase the accuracy of PIV analysis the floor of the target area was covered by a vinyl chloride plate and painted with an oil paint (to attempt to suppress light reflection as much as possible).

The edge of the target area, which corresponds to the shoreline of this experiment, was defined as the origin of the X and Z axes, and the center line of the target area was defined as the origin of the Y axis (see Fig. 1).

Fig. 1. Tsunami Wave Basin. The blue area represents the still-water section, the brown section the slope, and the grey part is the area where the Particle Image Velocimetry (PIV) analysis was conducted. The small grey square represents the model of the rectangular building. Red circles show the location of the wave gauges and electromagnetic current meters.
2.2 Measuring instrumentation

In the first instrumental configuration a total of six capacitance-type wave gauges (WG, manufactured by Kenek, Japan) were used to measure the time history of water surface elevation. Four of them were installed in the offshore area and two in the land side. Two electromagnetic current meters (ECM, manufactured by Kenek, Japan) were also installed at the same position as WG2 to measure the flow velocity. The sampling frequency of WGs and ECMs was set to be 200 Hz. The positions of these instruments is summarized in Fig. 1 and Table 1.

In the second instrumental configuration a high-speed camera (High speed camera K4, manufactured by KATO KOKEN Co., Ltd., Japan-) mounted above the basin was used measure the change in spatial distribution of velocity. In order to capture the water movement around the structure as precisely as possible the authors floated styrene beads with a particle size of 0.3-0.6 cm (which effectively work as tracers for the PIV analysis) evenly over the sea area before generating the tsunami wave. The sampling frequency of the high-speed camera was set to be 200 Hz. The captured images were analyzed by using a high-performance fluid analysis software (FlowExpert2D2C, KATO KOKEN Co., Ltd., Japan), and converted to a plane flow velocity field.

To make a comparison among cases easier, the authors defined the timing at which the water level at position of WG1 exceeds 0.5 cm as the start time for the analysis (i.e. at this moment $t = 0.0$ s).

Tab. 1. Instrumentation used in the experimental tests.

<table>
<thead>
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<th>Instrument name</th>
<th>Instrument identification tag</th>
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<th>$y$ (m)</th>
<th>$z$ (m)</th>
</tr>
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<td>0</td>
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</tr>
<tr>
<td>WG2</td>
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<td>-</td>
</tr>
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<td>CHT6-30-4</td>
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<td>0</td>
<td>-</td>
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</table>

2.3 Layouts of buildings

Rectangular wooden prism with a length of 0.1m, a width of 0.1m, and a height of 0.2m were used to represent the buildings. The edge of the models was covered by a vinyl chloride tape in order to make the roughness of its surface closer to that of the slope surface.

Three different layouts (single building, two buildings arranged parallel to the shoreline, and two buildings arranged perpendicular to shoreline) were tested (Fig. 2.). For the cases of the parallel and perpendicular layouts, the gap widths were also varied from 0.05m to 0.3m (in 5 cm increments). In all cases the first building model was placed 0.2 m away from the shoreline.

For the cases when no buildings were present or there was only one (single layout), the experiment was repeated five times, while all other cases were repeated three times (regardless of whether it was for the first or second instrumental configuration). By conducting the experiments multiple times it was possible to confirm that the maximum values of water level and flow velocity recorded at each
run were always within a 5% difference from the averaged value over all runs. Thus, the authors used the results of the first run of each case for the subsequent analysis that was conducted on water level changes. However, the authors used the result having the highest spatial and temporal integral value of the Luminance correlation coefficient (a coefficient related to the accuracy of PIV analysis) among each run for the PIV analysis.

3 Results

3.1 Wave Conditions

The time histories of the water surface elevation recorded at WG2, WG3 and WG5 are shown in Figure 3. As the waves progressed along the tank they underwent shoaling and their height gradually increased. The wave height was maximum at position X = -2.0 m (WG4), and broke between X = -1.0 m (WG5) and X = 0.0 m (WG6), where the wave height dropped sharply. The wave arrived at position X = -4.0 m (WG2) at t = 1.0 s, and eventually reflected from the tank edge at t = 13.3 s.

Hereafter in the analysis the part between t = 3.7 s to t = 4.47 s will be referred to as the first wave, and from t = 4.47 s to t = 5.52 s as the second wave (see Fig. 3). The maximum wave height at X = 0.0 m (WG5) was 5.5 cm, and at X = 0.8 m (WG6) was 4.5 cm. Therefore, the wave height hitting the structures (X = 0.2 m) was considered to be about 5 cm. The maximum velocity at X = 0.2 m was 2.40 m/s from the result measured by PIV.

![Fig. 3. Time series plots of the water elevation for the case when no buildings are present. The blue line represents the wave time history at X = -4.0m (WG2), the red dashed line at X = -2.0m (WG3), and the green line at X = 0.0m (WG5).](image)

3.2 Bow waves and wake waves

Figure 4 shows the snapshots taken by the high-speed camera for the single building case. The blue line shows the position of the bow wave, and the red line the wake wave. For the single building case, the incident wave reached the analysis area at around t = 4.1 s, and immediately after it touched the building a bow wave was formed in front of it. At around t = 4.5s the flow that had separated due to the presence of the building merged again behind it, and generated a wake wave (see Fig. 4 (a)). At t = 5.2s, the second wave arrived at the building and a bow wave was generated again (see Fig. 4 (b)). However, in this case the wake behind it had a different angle to that observed during the first wave.

Figure 5 shows the snapshots taken for the parallel layout cases. Figs. 5 (a) (b) show the results when the gap was 5cm, while Figs. 5 (c) (d) show those were the gap was 30 cm. When the wave reached the buildings a bow wave was generated. For the case when the gap was 5cm, the bow waves merged at t = 4.5s, and became one big bow wave (see Fig. 5 (a)). The generated bow wave made it difficult for the subsequent water mass to enter the gap and blocked the water intrusion to some extent. In contrast, when the gap was 30 cm the bow waves generated in front of the buildings did not completely merge. As a result, the incoming tsunami flow was not significantly reflected. Instead, it
concentrated at the center of the gap and accelerated as it passed between the buildings (see Fig. 5 (c)). When focusing on the flow behind the buildings, although two distinct wake waves could be observed for the case when the gap was 30 cm, a more complex form of the water surface was observed when the gap was 5 cm (were the wake waves overlapped (compare Fig. 5 (b) and (d)).

Figure 6 shows the snapshots taken for the perpendicular layout cases. When the gap was 10 cm, the incoming tsunami wave did significantly enter the space between the two buildings, and a bow wave did not develop between them (see Fig. 6 (a), (b)). In contrast, for the case were the gap was 20 cm (see Fig. 6 (c), (d)), the incoming tsunami approached the gap with a higher velocity and a hydraulic jump was generated when the water coming from both sides collided. Furthermore, a bow wave also formed in front of the inland side of the building.

![Flow conditions taken with the high-speed camera in the single building case. The grey box represents building model. The blue line represents the position of bow wave. The red line represents the position of wake wave. (a) t = 4.5s (b) t = 5.2s](image1)

Fig. 4. Flow conditions taken for the parallel layout cases (gap=5cm,30cm). (a) parallel layout gap = 5cm, t = 4.5s (b) parallel layout gap = 5cm, t = 5.2s (c) parallel layout gap=30cm, t=4.5s (d) parallel layout gap = 30cm, t = 5.2s
3.3 Velocity field

The spatial distribution of flow velocity is shown in Figures 7, 8, and 9. Here, the flow velocity was normalized to the value recorded for the case when no buildings were present. The left figures correspond to the results at $t = 4.25-4.50$ s, and the right ones show the results of $t = 5.25-5.50$ s.

In all cases, the flow velocities immediately in front of the buildings were found to be nearly zero. Areas having relatively lower velocity were also found adjacent to the back of the buildings. For example, for the single building case, when focusing on the area $x = 30–50$ cm, and $y = 0$ cm, the flow velocities decreased by 70% compared with those recorded in the case with no buildings at $t = 4.25-4.50$ s (see Fig. 7 (a)).

For the parallel layout cases, although the velocities right in front of and behind the buildings were reduced, those behind the gap were clearly increased. Although the changes were not so significant at $t = 4.25-4.50$ s, (Fig. 8 (a) (c)), at $t = 5.25-5.5$ s the flow velocity behind the gap increased by around 30-40% (Fig. 8 (b) (d)). When focusing on the perpendicular layout, for the case when the gap was 30cm, the area having lower velocities was found to spread widely around $x = 30 - 50$ cm (the space between the two buildings, see Fig. 9 (c) (d). In contrast, for case where the gap was 5cm (Fig. 9 (a) (b)), such a wide low-speed zone was not formed on the front of the inland side building. This is probably due to the fact that for the case when the gap was only 5cm the flow could not significantly enter the space, and neither a hydraulic jump nor a bow wave were generated in front of the inland side building.

In all cases there was an area behind the buildings where the flow velocity was reduced by more than 20% (hereinafter referred to as the low speed area), which was always more than 20 cm in length.
Fig. 7. Velocity field obtained from surface PIV analysis for single building case. The black cross indicates the position of WG6.
(a) average value from $t = 4.25s$ to $t = 4.5s$ (b) average value from $t = 5.25s$ to $t = 5.5s$

Fig. 8. Velocity field obtained from surface PIV analysis for parallel layout cases (gap = 5, 30cm). The black cross indicates the position of WG6.
(a) parallel layout gap = 5cm, average value from $t = 4.25s$ to $t = 4.5s$ (b) parallel layout gap = 5cm, average value from $t = 5.25s$ to $t = 5.5s$
(c) parallel layout gap = 30cm, average value from $t = 4.25s$ to $t = 4.5s$ (d) parallel layout gap = 30cm, average value from $t = 5.25s$ to $t = 5.5s$. 
3.4 Time histories of inundation depth, velocity and momentum flux

Figure 10 shows the time histories of flow depth, flow velocity and momentum flux at WG6 \((x = 0.8\text{ m})\) for the cases when no buildings are present, and when the parallel layout gap is 5 cm and 30 cm. Here, the momentum flux \(M\) was calculated by the following equation.

\[
M = h \times v^2
\]

where \(h\) is the flow depth recorded by WG6, and \(v\) is the flow velocity obtained by PIV. For the case were the parallel layout gap is 5 cm, the flow depth increased more slowly than in the other cases (see red break line in Fig. 10 (a)). As a large bow wave was generated in front of the buildings, the subsequent water mass could not easily enter the gap between them. However, the flow depth became higher after the second wave arrived, and generated two wake waves that overlapped near the measurement point.

For the case when the parallel layout gap was 30 cm the water level rose more quickly than in the other cases (see green dash line in Fig. 10 (a)), as the incoming tsunami accelerated when it passed between the two buildings. The maximum value of the flow velocity was almost the same among the three cases considered (see Fig. 10 (b)). However, when the parallel layout gap was 5 cm the flow velocity dropped more rapidly after it reached its maximum value, due to the effect of the bow waves. In addition, after \(t = 4.5\) s, when the wake waves overlapped, the flow velocity became much slower than in the other cases. As a result, the maximum value of the momentum flux for the case when the gap was 5 cm was about 40% smaller compared with the case were no building was present, and about 140% for the case when the gap was 30 cm (as shown in Fig. 10 (c)). From this, it can be said that the maximum value of the momentum flux behind the gap is greatly influenced by the size of the gap.

Time histories of flow depth, flow velocity and momentum flux at WG6 \((x = 0.8\text{ m}, y = 0.0\text{ m})\) for the cases when there is a single building, a perpendicular layout with gaps of 5 cm and 20 cm are shown in Fig. 11. There was no significant difference in the recorded flow depths between \(t = 4\) s and 4.4 s among these four cases (see Fig. 11 (a)). The maximum flow velocity was slightly larger for the single building case compared to the others (see Fig. 11 (b)). After \(t = 4.3\) s, the flow velocity for the case when the perpendicular layout gap = 20 cm became smaller than the others, as the measurement
point was included in the low speed area (as explained earlier). The maximum values of the momentum fluxes for the cases of a single layout and a perpendicular layout gap = 5cm were almost same, and in both cases they reached the maximum values after the second wave arrived (Fig. 11 (c)). In these cases, although the velocities reached the maximum values when the first wave arrived, as the flow depths were not high during this time, the momentum fluxes did not reach a maximum until the arrival of the second wave. Comparing the maximum fluxes, the value for the perpendicular layout when the gap was 20 cm was found to be clearly lower than the other cases, around 30% less than in the case when no buildings were present. The reason why the momentum flux of the second wave was not significantly increased in this case is that the measurement point was included in the low speed area, and thus the flow velocity did not increase substantially.

Fig. 10. Time series plots of the experiment at X = 0.8 m (WG6) for the parallel layout case. The blue line represents the case with no buildings present, the red break line represents parallel layout with a gap = 5 cm case and the green dashed line represents the parallel layout with a gap = 30 cm case. (a) Inundation depth. (b) Velocity. (c) Momentum flux

Fig. 11. Time series plots of the experiment at X = 0.8 m (WG6) for the single and perpendicular layout case. The blue line represents the single case, the red break line represents a perpendicular layout with a gap = 5 cm case and the green dashed line represents perpendicular layout with a gap = 20 cm case. (a) Inundation depth. (b) Velocity. (c) Momentum flux
4 Discussion

The mitigation of tsunami forces on critically important buildings is an important topic in disaster risk management. Particularly, it can be important to shelter critically important buildings such as tsunami shelters, in order to ensure that they can help in the preservation of human life. Tsunami evacuation simulations have shown the importance of such buildings (Shibayama et al., 2013, San Carlos-Arce et al., 2017, Okumura et al., 2017, Takabatake et al., 2017, 2018), with the present experiments highlighting the importance of carefully considering the layout of other structures around them.

In the present experiment, the maximum value of the momentum flux at the measurement point \( X = 0.8 \text{m} \) (WG6) was the lowest for the case when the perpendicular layout gap was 30 cm. This is the case where a building is place right in front of measurement point \( X = 0.8 \text{m} \) (WG6). Therefore, placing a sturdy structure in front of a building of critical importance (e.g. tsunami shelter) could decrease the tsunami force acting on it. However, to achieve this, the offshore structure would need to be sufficiently strong that it is not destroyed by the incoming tsunami’s force. If the offshore building is destroyed by the tsunami, they could overturn or even become a drifting object and collide with important buildings behind it. This is what happened, for example, in Onagawa town, during the 2011 Tohoku Earthquake Tsunami (see Mikami et al., 2012). Flow conditions around the building group may be affected by parameters such as building width, building length and Froude number, but in this experiment these parameters were kept constant. Therefore, it is necessary to conduct an experiment in which these are changed, and also more complex arrangements of buildings are considered. In addition, if there are drifting objects in a flow field, flow patterns could become more complex, and such effects should be considered in future work.

5 Conclusion

Physical experiments were conducted to clarify the change in flow patterns due to the different arrangement of coastal buildings, measuring changes in the flow velocity, inundation depth and momentum flux around structures. Froude number of hydraulic experiments was 3.0.

The main findings obtained from the results of hydraulic experiments are shown below.

1. The shape of bow waves and wake waves around buildings changed significantly, according to the various building layouts considered.
2. The length of the area where the flow velocity behind the building was low (at least 20% lower than in front of it) was always at least twice the length of the building side, regardless of the layout of adjacent buildings.
3. Changes in the shape of the bow and wake waves greatly affected the time series characteristics of inundation depth and velocity. As a result of this, the momentum flux for the various building layouts varies between 30% and 140% (compared to the case when no buildings were present in the tank).
4. The results of the maximum value of the momentum flux showed that placing a sturdy structure in front of a building of critical importance (such as a tsunami shelter) could reduce the tsunami force acting on it. In particular, the reduction effect might be high when the distance between the important building and the sturdy structure was smaller than about twice the width the sturdy structure.

Such results are important for disaster risk managers to design better buildings in tsunami-prone areas, and can help improve the layout and design of evacuation buildings.

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References


