Laboratory experiment study on the building relative angle against tsunami waves

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1. Introduction

Tsunami inland penetration with strong inundation flow causes damage to infrastructures, forests, buildings and humans. The current design standards for building are considered to resist to an extraordinary lateral load induced by seismic action or strong winds. However, the coastal buildings are rarely designed to withstand hydrodynamic forces. Tsunami wave forces on buildings are highly variable and depend on both the wave conditions and the type of structure being considered. There several laboratory experiments have been conducted to investigate the impact of dam-break and tsunami-like bore waves on structures such as Chanson [2006], Matsutomi and Okamoto [2010] and Wuthrich et al. [2016]. However, most of studies were either concentrated on a vertical wall building or building with percentage of porosity. There are no studies on the impacts of both dry and wet bed tsunamis on the building which has relative angle to the incoming waves. Therefore, the cause and mechanisms of tsunami-induced forces on such buildings under extreme loading are still remained challenging to further investigation. The main objective of this study is to insight identify the mechanisms of the interaction between tsunami waves and buildings with both of different wave conditions and building conditions by a series of laboratory experiments. The outcome results might help to better design or plan for the coastal residents buildings against the tsunamis wave impacts in the future.

2. Experiment setup and methodology

Figure 1 is the sketch of current laboratory experiment setup. The tsunami like-waves are generated using the vertical sudden release technics of a water volume from a higher head to a lower channel on a dry-bed and wet-bed conditions. This technic is similar to the dam-break experiments that have been carried out by many other researchers such as Chanson et al. [2006], Lukkunaprasit et al. [2009], Meile et al. [2013] and Wüthrich et al. [2017]. The wave propagates on a horizontal smooth channel with a total length of $L = 14.6$m and a width of $W = 0.3$m. The buildings with a height of $H_b = 0.3$m and width of $B = 0.1$m were located in 11m from the release gate. The blockage ratio $\beta = W/B = 3$ is sufficient to avoid the wall side effects to the building. A video camera was setup to measure the water level around the building. There are four ultrasonic water level sensors with a high frequency of 100 Hz were setup to measure the details of tsunami wave height during the experiments. The water level signal post-processing is able to compute the wave front celerity (U) of propagating tsunami waves. The wave propagating on a dry bed can represent for the first incoming tsunami wave, whereas a wet bed bore may represent any following inundation wave. These both phenomena are important since past tsunami inundation events showed that the maximum resulting force may not always be

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associated with the first incoming wave-induced inundation. Figure 2 are some preliminary tests of dry-bed surges and wet-bed bores on a vertical building.

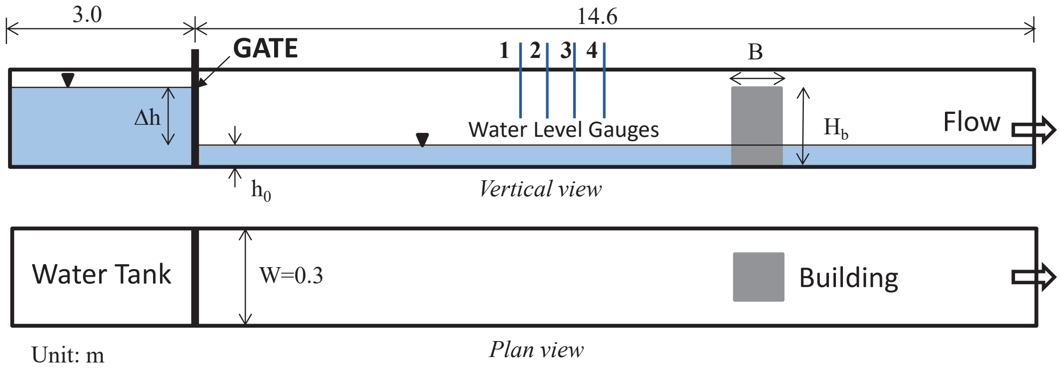

Figure 1. Experiment configuration sketch

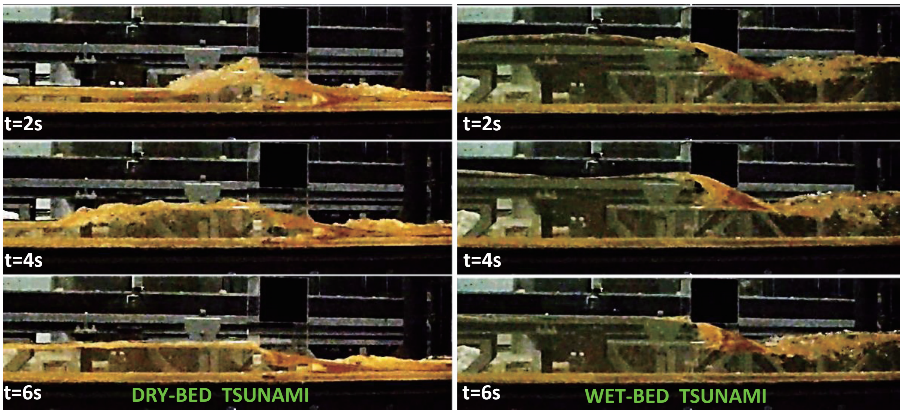

Figure 2. Laboratory tests of dry- and wet-tsunami waves

The main objectives of the current laboratory experiment tests are to analyze the tsunami load on the buildings which have different angles to the incoming wave. Therefore, there two group of tests were conducted. Firstly, the group tests are conducted without the presence of building to investigate the generated dry- and wet-tsunami wave characteristics such as wave height, wave front celerity. The second tests are done with the building.

3. Results and discussions

3.1. Generated tsunami waves characteristics

The detailed tsunami wave profiles were measured from four different water sensor devices along the channel. The consecutive distances between each water level gauges from the WG-01 to WG-04 are 32cm, 28.5 cm, and 30.5cm respectively. The time series of the wave profiles for the wet-bed (Run 01) and dry-bed (Run 06) are presented in Figure 3. The tsunami wave height in the wet-bed cases seems always higher than in the dry-bed cases. Based on the time occurrence of water level in each water gauge, the tsunami front celerity (*U*) is calculated and shown in Table 1. The averaged front celerity of the wet-bed and dry-bed cases is equal to 1.4 m/s and 1.1 m/s, respectively. Based on these wave front celerity (U), both the Reynolds (R_e) and Froude (F_r) numbers of the flow were calculated using the expressions presents in Table 1, where D is the hydraulic diameter, ν the kinematic viscosity of water, g the gravity constant and h_{max} the maximum water depth. The relatively high values of the Reynolds number for both wet and dry beds indicate a high level of turbulence inside the wave. For all of cases, the Froude number is greater than 1 implying that the flow is supercritical or rough regimes. For the dry bed, higher values of the Froude number were greater than 2.0 indicating the flow behind the wave front in these cases were saturated with advected eddies (Yeh [2007]).

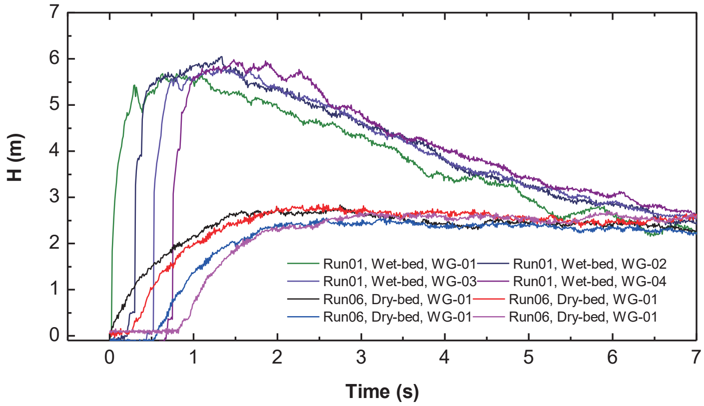

Figure 3. Measurement results of wet-bed and dry-bed tsunami wave height from 4 ultrasonic water level sensors

Table 1: Experiment testcases without the presence of building

	Bed condition	Δh (cm)	h_{max} (cm)	H_{max} (cm)	U (m/s)	$R_e = \frac{U*D}{\nu}$	$F_r = \frac{U}{\sqrt{g*h_{max}}}$
Run 01	Wet, $h_0 = 5$cm	15	10.9	5.9	1.5	3.67E+05	1.4
Run 02	Wet, $h_0 = 5$cm	15	12.2	7.2	1.2	3.30E+05	1.1
Run 03	Wet, $h_0 = 5$cm	15	10.9	5.9	1.6	4.07E+05	1.6
Run 04	Wet, $h_0 = 5$cm	15	12.4	7.4	1.4	3.69E+05	1.2
Run 05	Wet, $h_0 = 5$cm	15	12.4	7.4	1.3	3.53E+05	1.2
Run 06	Dry, $h_0 = 0$cm	15	3.0	3.0	1.2	1.13E+05	2.1
Run 07	Dry, $h_0 = 0$cm	15	3.0	3.0	1.1	1.12E+05	2.1
Run 08	Dry, $h_0 = 0$cm	15	3.0	3.0	1.1	1.03E+05	2.0
Run 09	Dry, $h_0 = 0$cm	15	3.0	3.0	1.1	1.08E+05	2.0
Run 10	Dry, $h_0 = 0$cm	15	3.0	3.0	1.1	1.07E+05	2.0

3.2. Impacts of tsunami wave on the buildings

In order to investigate the impact of tsunami on the building, four cases were setup and tested with the same initial conditions of the tests in section 3.1. For the wet-bed cases, the initial water depth is set to 5cm. For each bed condition cases, the building was tested by changing the angle to the incoming wave from 90^o to 45^o. Table

2 is summarized of all experiment building testcases. Figure 4 shows an example of some snapshots of water surface variations during the experiments. In general, from these data analysis, the dry bed and wet bed tsunami had a different characteristic. Dry bed cases are characterized by non-aerated front followed by the increasing of flow depth, while wet bed cases show a sudden increase in wave height with stronger turbulent aerated roller front. A very high splash was obtained during the wet-bed cases when the building is directly faced to the incoming wave Case 03 (Figure 4b). These results are also indicated that the different mechanisms of tsunami-induced forces on the angled buildings during the dry- and wet-bed tsunami wave and needed to further clarify in this study.

Table 2: Experiment of building testcases

	Bed condition	**Building condition**		
		Width, *B* (cm)	**Height, H_b (cm)**	**α (DEG)**
Case 01	Dry, $h_0 = 0$cm	10	30	90
Case 02	Dry, $h_0 = 0$cm	14	30	45
Case 03	Wet, $h_0 = 5$cm	10	30	90
Case 04	Wet, $h_0 = 5$cm	14	30	45

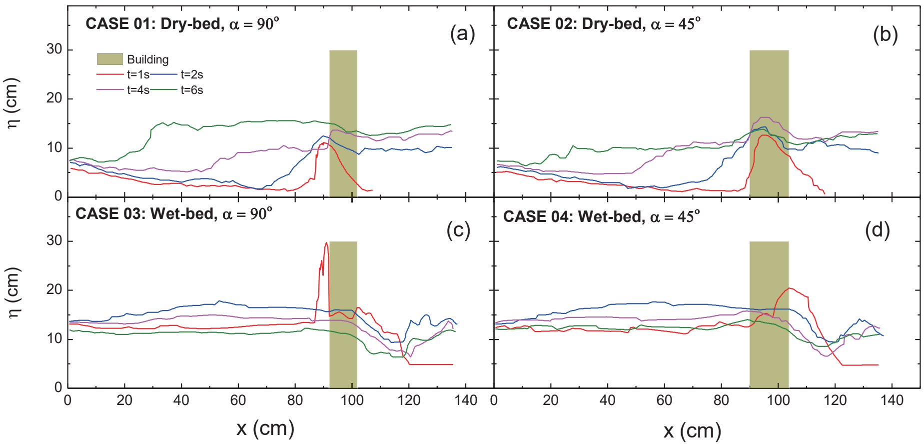

Figure 4: Snapshots of the water surface variations for four Cases

3.3. Vertical run-up height on building

The information of vertical run-up height on the building is important information for estimate the impacts of tsunami. The vertical run up heights, H_r, which were measured by the video camera from four Cases, are compared with the maximum wave profile H_{max} measured without the building for both a dry bed and a wet bed (Figure 5). This ratio implies that the relatively maximum run-up height on the building compare to the maximum wave height without the building. For the dry bed, the maximum run-up height on both $\alpha = 90^o$ and $\alpha = 45^o$ cases show about 3 times higher the maximum wave height without the building. However, for the wet bed cases, the larger initial impact by the run-up splash caused the run-up height is approximately 5 times compare to the maximum wave height without the building during the Case 03 (Figure 5b). Overall, the run-up height on the α = 45° building are higher than on the α = 90° building case for the dry bed tests and lower for the wet bed case.

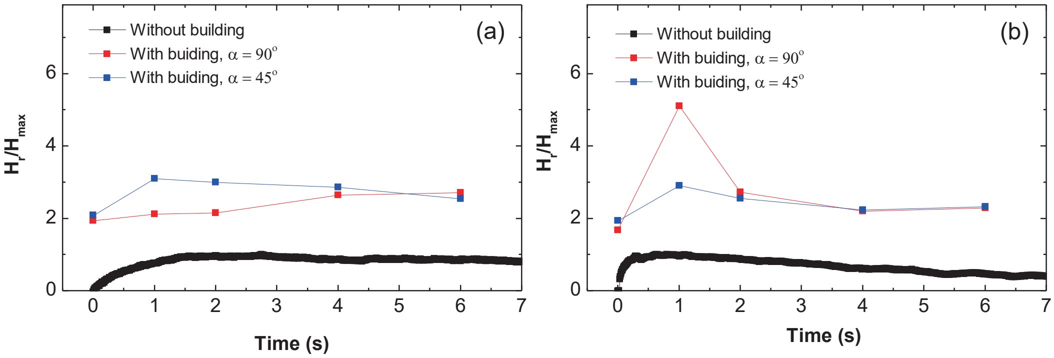

Figure 5. Vertical run-up height (a) Case 01: Dry-bed, (b) Case 03: Wet-bed

3.4. Estimation of tsunami horizontal forces

During the tsunami wave impact, the horizontal force F_x component is more dominant so the estimation if tsunami horizontal forces is needed to ensure the survival of building during the extreme event. The estimation of the horizontal force produced by a flow against a structure can be predicted using the method proposed by Morison et al. [1950]. This Morison formula was taking into account a hydrodynamic component (or drag component) and an inertia component. However, the inertia component can be neglected due to the long periods of tsunami wave. The equation of hydrodynamic component in the *x* direction is expressed as,

$$F_x = \frac{1}{2}\rho C_D B(hU^2) \tag{1}$$

where ρ is the water density, *B* the building width, *h* the flow height and *U* the wave front celerity, C_D is drag coefficient depending on the obstacle geometry and on the flow conditions.

According to Blevin [1984] the values of drag coefficient C_D for 45-angled and 90-angled cube equals to 0.80 and 1.15, respectively. Wuthrich et al. [2017] proposed a similar formula but using the difference resistance coefficient C_R instead of drag coefficient C_D to consider to the hydrostatic pressure difference between the back and front of the building. However, he used the measured wave height without the structure and depth-averaged current velocity for the calibration and the best agreement obtained as $C_R = 2$ with his experiments. For our preliminary analysis of the tsunami horizontal forces in this study, we utilize the traditional Morison formula for the calculation. The comparison results of horizontal forces, F_x, for the dry bed (Case 01) and wet bed (Case 03) are shown in Figure 6. The red-line is a time evolution of the horizontal force without the presence of building which used the wave height measured from the water gauge; the blue line is the force acting on surface of building which has α = 90° to the incoming waves; and finally the pink line is the force on building as α = 45°.

In general, the horizontal tsunami induced forces in the wet-bed cases are larger compared to the dry bed tsunami cases. It is obviously that the calculated horizontal forces by the wave run-up height on the building are much higher than in case of without the presence of building. During the dry bed tsunami tests, the horizontal force on the rotating building (α = 45°) was higher than in the test when the building is directly faced to the incoming tsunami waves (α = 90^o). However, there was a distinguish difference for the wet bed cases. The maximum of horizontal force was associated with the maximum of splash height at the initial stage when tsunami wave impacted to the building during the case of building angle α = 90^o. Whereas, a similar the splash mechanism was not obtained as the building rotated 45^o to the income wave direction (Figure 6b)

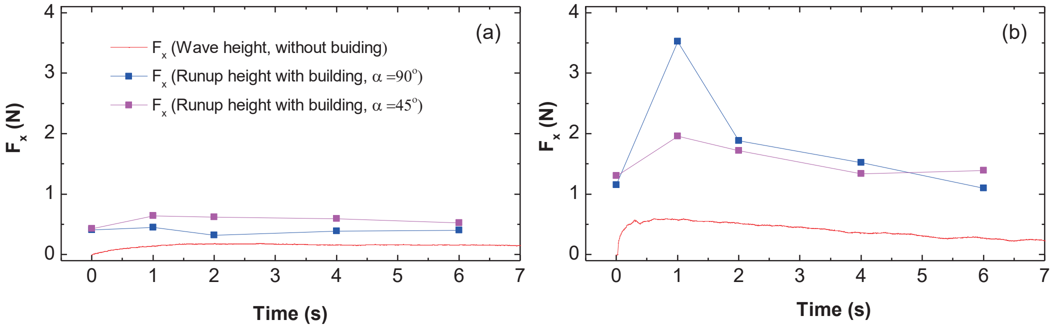

Figure 6. Tsunami horizontal forces (a) Case 01: Dry-bed, (b) Case 03: Wet-bed

4. Conclusions

A series of laboratorial experiments on the building relative angle against tsunami waves were conducted. The building conditions are tested with both dry bed and wet bed conditions. The propagating wave on a dry bed can represent for the first incoming tsunami wave, whereas a wet bed tsunami may represent any following inundation wave. The results from this study indicate that although the hydraulic head, Δh, is set the same for both dry and wet bed conditions but the wave height at the measurement points are not the same. The wave height in the wet bed condition is always larger compared to the dry bed cases. To access the tsunami impacted forces on the building, this study assumed to use the wave front celerity and water level as inputs conditions. The results have shown that the building relative angle against tsunami waves can help to reduce the force on the building during the wet bed tsunami. However, a further detailed measurement of the run-up height, velocity field and force measurement in front of building are needed for more reliable estimation of tsunami induced forces on the building.

5. References

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