AN EXPERIMENTAL STUDY ON THE TSUNAMI PRESSURE ACTING ON PILOTI-TYPE BUILDINGS

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It is known that piloti-type structures, which have an open space on the ground floor, have advantages for tsunami hitting because tsunami can pass through the ground floor. There is a basic guideline for the design of piloti-type structures for tsunami forces but detailed information such as tsunami forces acting on the elevator hall or the ceiling is not speculated. Then, the hydraulic physical model tests were performed by using a newly-developed tsunami wave generator. As a result of the physical model tests, the tsunami force acting on an upper structure becomes significantly smaller compared with a normal (not piloti-type) structures. It should be noticed that tsunami reaches the upper structure and gives the significant tsunami force on the upper structure because the ground structure exists, even if the peak water level is somewhat lower than the ceiling level of the ground floor. The uplift force observed on the ceiling in front of the ground structure is much larger than the usual design force on the ceiling of the buildings.

Keywords: tsunami force; piloti-type structure; hydraulic physical model test

INTRODUCTION

Recently, several major tsunami events have caused huge economic losses and catastrophic devastation to human lives and infrastructures. For instance, the Sumatra Earthquake and Indian Ocean Tsunami on 26 December 2004 caused serious damage to the extensive coastal areas in Indian Ocean and claimed over 220,000 lives. A lot of houses and coastal facilities including coastal dykes and ports were destroyed (Saatcioglu et al. 2006). The Tohoku Earthquake and Tsunami on 11 March 2011 caused severe damage to the pacific coast of the northern part of Japan and claimed over 19,100 lives. In this disaster, a lot of houses and buildings located near the shorelines, especially in Iwate, Miyagi and Fukushima prefecture, were severely damaged and swashed away as well as coastal infrastructures (Mori and Takahasi 2012, Anawat et al. 2012). According to the filed surveys carried out after the 2011 Tohoku tsunami, it was clarified that even some reinforced concrete structures were not able to resist extreme tsunami forces and turned over (Kakinuma et al. 2012). Photo 1 shows an example of damaged RC buildings whose foundation piles were pulled out. The most basic strategy for the mitigation of the tsunami risks is to evacuate to higher ground areas above tsunami inundated areas. However, there are some places that have no higher ground areas. Thus, the existence of reliably resistant buildings against tsunami is required in order to prevent the lives and property from tsunami.

It is known that large tsunami pressure acts on lower floors of a building. Then, piloti-type buildings, which have an open space on the ground floor, have advantages for tsunami hitting because tsunami can pass through the ground floor. The authors have been proposing the piloti-type building whose ground-floor walls can be removed by tsunami, named “T-buffer”. Figure 1 shows the snapshot of the tsunami simulation for the T-Buffer and the normal building.

In Japan, there is a basic design guideline for tsunami resistant buildings (National Institute for Land and Infrastructure Management 2012). This guideline includes a formula for tsunami force applied to a piloti-type building (Fig. 2(b)). In the formula, the effects of open space are taken into consideration. Although a piloti-type building has an open space on the ground floor, it usually has column structures on the ground floor such as an elevator hall. Apparently, when piloti-type buildings are designed, the influences of the tsunami forces acting on them should be considered. However, no detailed information about them is speculated in the guideline. In fact, the complex interaction between tsunami force and a piloti-type building, which has small structures on the ground floor, is still poorly understood.

The ultimate goal of our research is to clarify the complex interaction between tsunami forces and piloti-type buildings and to improve the current guideline for piloti-type buildings. With the objective in mind, in the present study, the hydraulic physical model tests were conducted to investigate tsunami forces acting on a piloti-type building.

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Photo 1. Structural damage due to tsunami in 2011 in Japan.

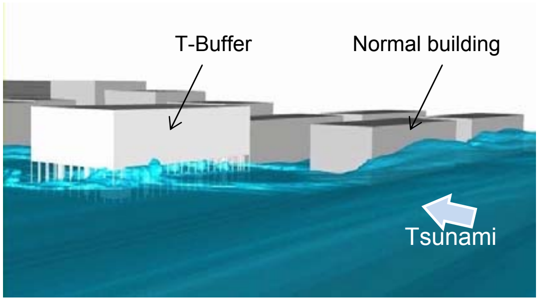
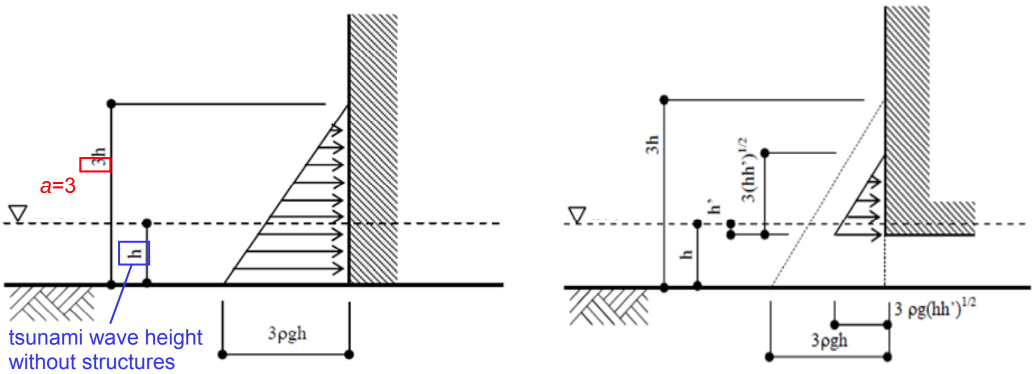


Figure 1. Tsunami simulation of T-Buffer.



(a) normal building **(b) piloti-type building**

Figure 2. Tsunami force acting on a normal building and a piloti-type building according to the guideline (2012).

SET UP OF EXPERIMENT

The physical experiments were performed with 1/40 model scale in a wave flume (0.8m wide, 1.6m high and 47m long) located at the Taisei Technology Center, Yokohama, Japan. Figure 3 shows the configurations of the experiments. A 1V:10H slope was installed at the downstream and the structure was placed on the landside area, 1.80m away from the shoreline.

In the experiments, three types of structures were considered; (S1) wall type, (S2) two box type and (S3) one box type. The S2 type structure consists of two boxes. The upper box (A) represents an upper structure of a piloti building. The lower small box (B), which is a rectangular column with the width of 0.188m and the height of D (= 0.188m), represents an elevator hall on the ground floor. The distance from the front face of (A) to the front face of (B), defined as L, was changed in 5 cases (L= 0.0D, 0.5D, 1.0D, 2.0D, 4.0D).

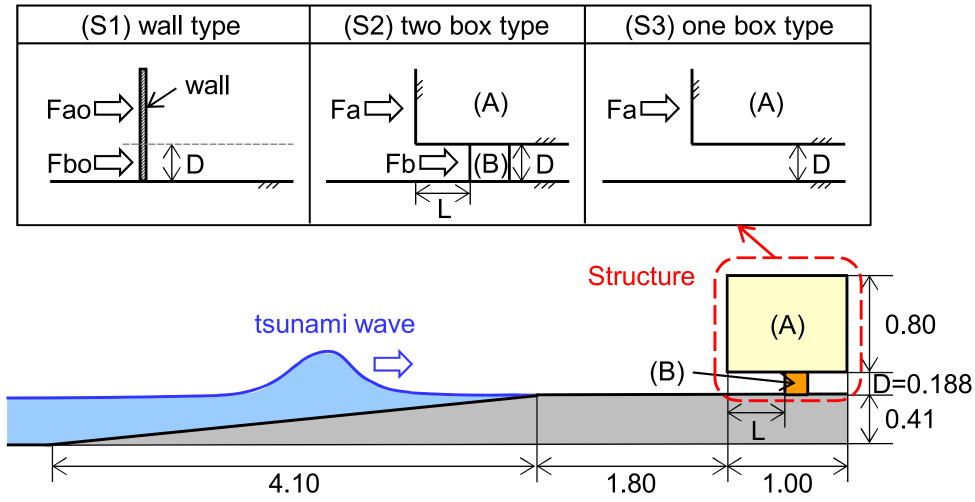


Figure 3. Set up of experiments (unit: m).

Tsunami waves used in the experiments were generated by our newly-developed tsunami wave generator (Fig.4). The generator is capable of generating about 40cm height tsunami as a maximum tsunami height in the case of 40cm initial water depth. It is also capable of reproducing arbitrary wave steepness by controlling the time intervals of opening six valves set on the top of the chamber. In the experiments, 12 different types of tsunami waves were employed by changing the initial water height in chamber *dH* and the timing of opening air valves *dt*. Tsunami conditions and structure conditions in the experiments are listed in Table 1.

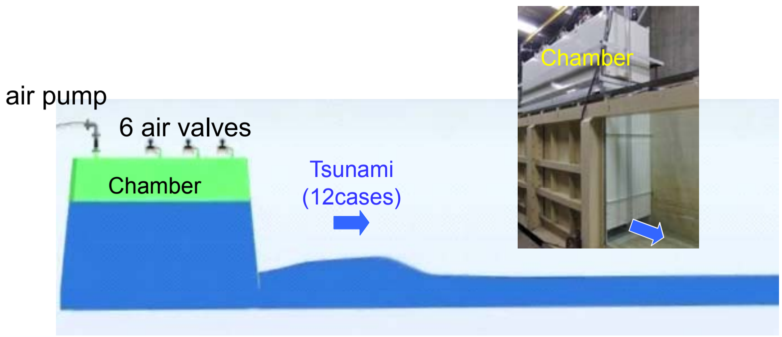


Figure 4. Tsunami wave generator.

Table 1. Experimental conditions.

Table 1(a). Tsunami wave conditions.

	value	notation
Initial water height in chamber	2.3m	dH23
	2.1m	dH21
	1.7m	dH17
	1.0m	dH10
Interval time of air valves	0.0s	t00
	0.8s	t08
	1.6s	t16

Table 1(b). Structure conditions.

type		location of (B)	notation
S1	Wall	-	D00W
S2	Two Box Type	L=0.0D L=0.5D L=1.0D L=2.0D L=4.0D	D00 D05 D10 D20 D40
S3	One Box Type	-	D99

Photo 2 shows the configuration of wave gauge and pressure gauges. To measure water surface elevation, one wave gauge was placed in front of the structure with a sampling rate of 1000Hz. Ten pressure gauges were attached on the front side of the upper structure (A) and five pressure gauges were attached on the front side of the lower structure (B). More than three pressure gauges were placed on the bottom surface of (A) to measure the uplift pressures. The diameters of all pressure gauges are 10mm and the distance between each pressure gauge was set 32 mm at minimum. The sampling rate for the pressure gauges was also 1000Hz in order to obtain the impulsive tsunami force.

By summing the measured pressures, the net base horizontal tsunami force acting on the front side of (A) (defined as F_a) and on the front side of (B) (=F_b) were obtained. And also, the net base vertical tsunami force acting on the celling in front of (B) (=F_s) was obtained with the same way.

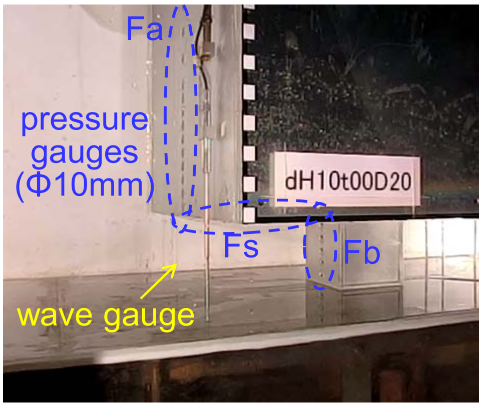


Photo 2. Configuration of the gauges

RESULTS AND DISCUSSION

Tsunami waves

At first, water surface elevations of every tsunami were measured at the point of the structure front without the structure (defined as H_0) in order to obtain every tsunami height and steepness. Figure 5 illustrates the time series of the water surface elevations of three cases. The tsunami shown in Fig.5 were generated in the cases where the initial heights in the chamber were the same value (dH =2.1m) but the interval times of air valves were set different (dt =0.0, 0.8 1.6s). The maximum tsunami heights are almost same and the values are about 0.18m. However, the wave steepness is different. In the case of t00, where all the six air valves on the top of the chamber were opened at once, the tsunami shape is relatively steeper. On the other hand, in the case of t16, where the air valves were opened one by one with 1.6s interval time, the water surface elevation gradually increase and the tsunami shape is relatively milder.

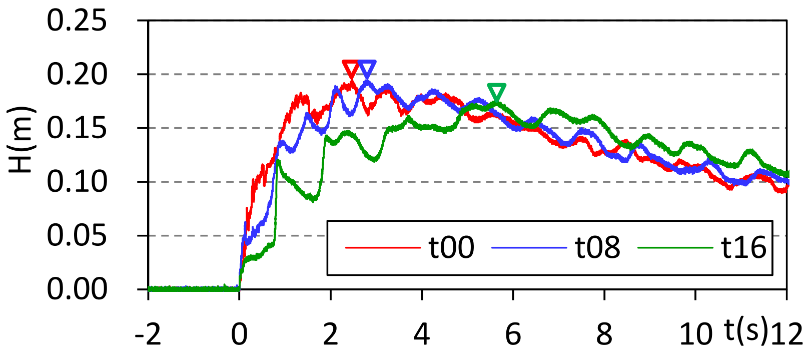


Figure 5. Tsunami waves without structures in the case of dH21.

Tsunami forces and water level

Figure 6 shows the time series of the water surface elevation H and the tsunami forces F_a, F_b and F_s in the case of dH21t00D40, where the tsunami shape is steeper. In the Fig.6, snapshots taken at the same instants as shown in the graphs are also presented.

At first, the tendency of time series of F_b and F_s looks almost same in this case. However, the tendency of F_a is apparently different.

At the moment tsunami reached lower structure (B) as shown in Fig. 6(a), F_b and F_s rapidly increased. At around 5.5s (at the time of Fig. 6(b)), tsunami reached the upper structure and both F_b and F_s had the maximum values. And also, at the almost same time, F_a started to increase. After tsunami reached the upper structure, both F_b and F_s decreased. On the other hand, F_a still gradually increased. Figure 6(c) shows the moment when the water was splashed and H became the highest. According to the guideline (2012), tsunami force can be estimated with the maximum tsunami height. However, as shown in Fig.6(c), there is a time difference between the occurrence of maximum tsunami height and maximum tsunami forces. After the splashed water came down (Fig. 6(d)), F_a had the maximum value.

The tendency mentioned above also applies to the other cases where tsunami shapes are steeper. From these results, it can be suggested that when tsunami is steeper, the time variation of tsunami forces on a pilloti-type building doesn't correspond to that of the tsunami height in front of the building.

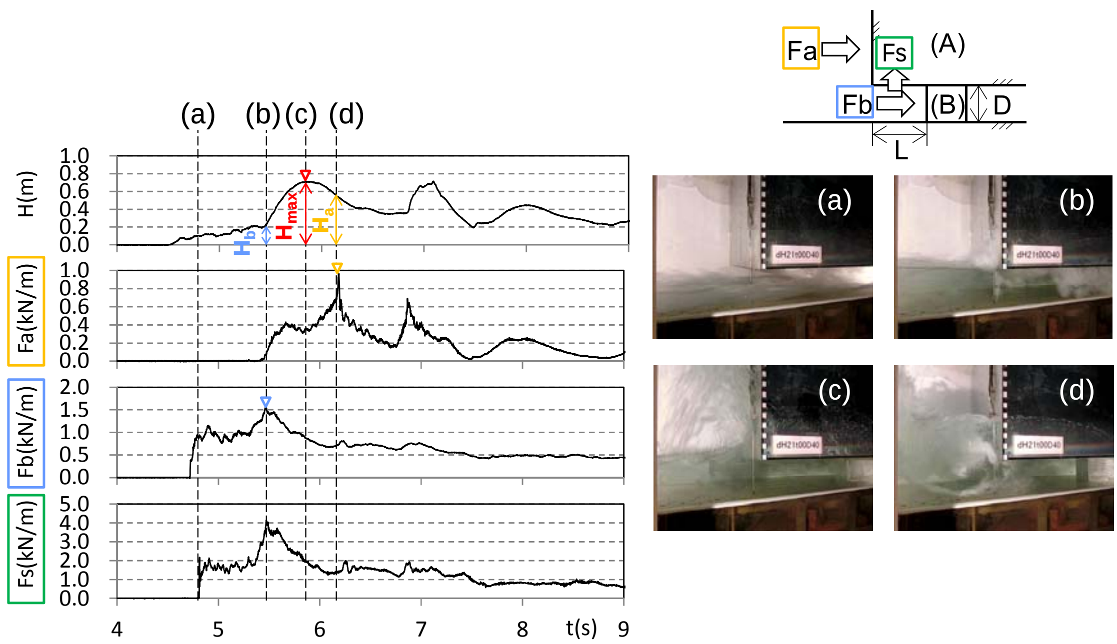


Figure 6. Time series of water level and tsunami forces in the case of dH21t00 (steeper wave).

Figure 7 shows the time series of the water surface elevation H and the tsunami forces F_a and F_b in the case of dH21t16D40, where tsunami shape is milder.

At the time of Fig. 7(b), the F_b had the maximum value but the F_a was still zero since the water surface didn't reach the upper structure. At around 9.6s, tsunami hit the upper structure and the F_a started to increase. When the tsunami height reached the maximum value, F_a had also the maximum value (Fig. 7(d)). In this milder tsunami case, the time series of F_a looks corresponding to that of H. Additionally, in this case, the splash of water in front of the upper structure wasn't observed because the water surface gradually increased. This may be a reason both the maximum H and maximum F_a were smaller compared with previous steeper tsunami case.

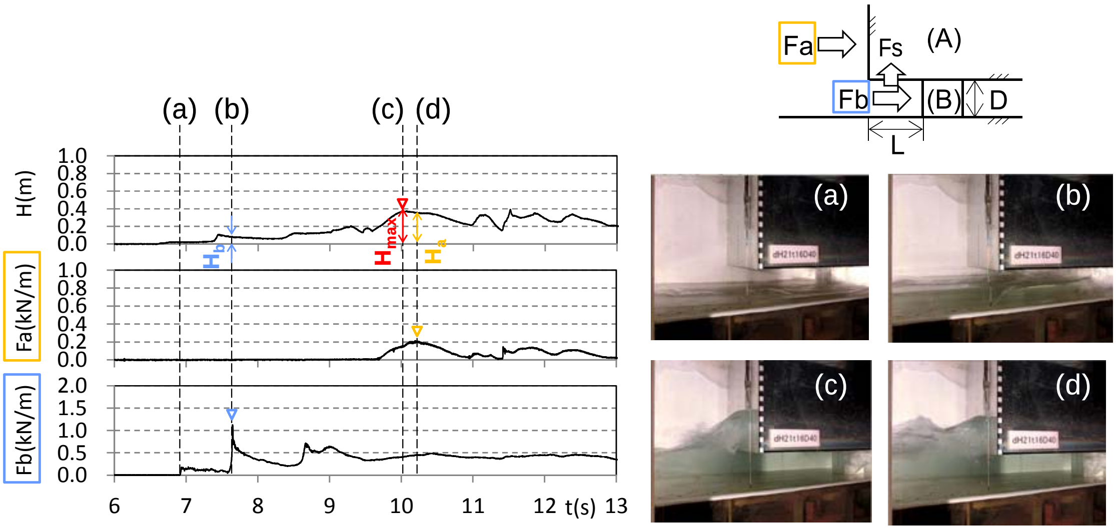
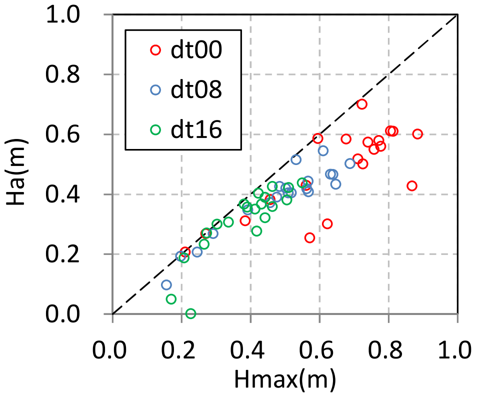


Figure 7. Time series of water level and tsunami forces in the case of dH21t16.

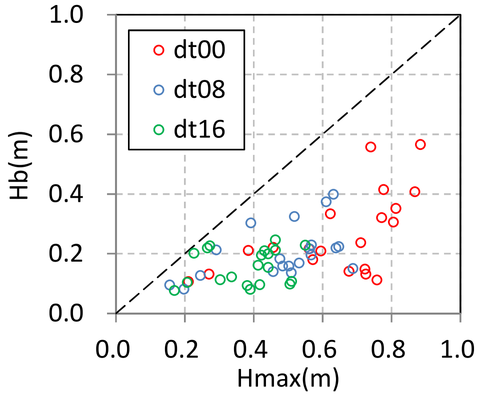
Figure 8 shows the comparison between the maximum tsunami height H_{max} and the tsunami height H_a, H_b, which were measured when the maximum F_a, F_b were recorded. Here, horizontal axis means H_{max} and vertical axis means H_a, H_b.

Figure 8(a) shows the results of the upper structure (A). When the H_{max} is less than about 0.45m, the H_a looks corresponding to H_{max}. On the other hand, when the H_{max} exceeds about 0.45m, H_a doesn't correspond to H_{max}. When H_{max} is more than 0.45m, the splash of water was observed at the initial impact of the upper structure. In this case, the maximum F_a occurred when the splashed water came down. This is the reason H_a doesn't correspond to H_{max}.

Figure 8(b) shows the results of the lower structure (B). Unlike the results of (A), the H_b does not correspond to H_{max} in almost all cases. Mostly, H_b are much smaller than H_{max} and locate at the range of 0.1m ~ 0.2m. Since the ground floor height is 0.188m, the results mean that F_b had maximum value when the water surface reached the ceiling of the ground floor.



(a) Upper structure (A)



(b) Lower structure (B)

Figure 8. Comparison between the maximum water level and the water level at the maximum F_a or maximum F_b.

Tsunami forces acting on normal building

According to the guideline (2012), the distribution of the tsunami pressure is assumed to be the same as the hydrostatic pressure. The height of the tsunami pressure is proportional to the maximum tsunami height without structures. Here, the proportional parameter is defined as "a". The guideline defines "a" is equal to 3 as shown in Fig.2. In the experiments, the tsunami forces acting on the wall (S1 in Fig. 3), were obtained by adding F_a and F_b. Maximum tsunami wave heights H_{0max} without structures were also obtained. Therefore, "a" in the experiments can be estimated by the following equation:

$$a = \sqrt{\frac{2(F_a + F_b)}{\rho g H_{0\max}{}^2}} \tag{1}$$

in which, ρ is the density of the fluid and g is the gravity acceleration. Estimated "a" in the experiments are plotted in Figure 9. Here, horizontal axis shows maximum tsunami wave height and vertical axis shows the number of "a". In the case of dt08 and dt16, the estimated "a" are nearly 3, which means a good agreement with the guideline. However, in the case of dt00, "a" exceeds 3 and the values are almost 4. dt00 is the case where tsunami wave is steeper and the tsunami force acting on the wall became maximum when the splashed water came down.

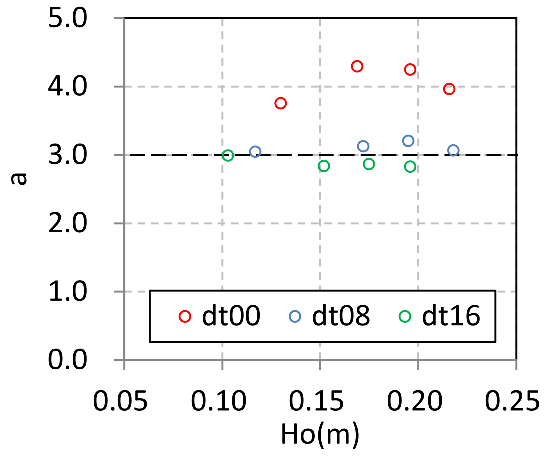


Figure 9. Estimation of parameter "a".

Tsunami forces acting on walls of piloti-building

Figure 10 shows the results of maximum F_a and maximum F_b. Here, horizontal axis shows the maximum F_a and F_b and vertical axis shows the structure type listed in Tab. 1(b).

Figure 10(a) shows the results of F_a. F_a of the normal building (S1) are much larger than that of the piloti-type building (S2 and S3) in all tsunami cases. It means when a building is piloti-type, the tsunami force acting on the building can be significantly decreased.

In two tsunami cases of H=0.169m and H=0.130m, the tsunami heights are lower than the ground floor height (=0.188m). Therefore, if there is nothing on the ground floor, tsunami goes through without reaching the upper structure (A). In fact, when the lower structure (B) doesn't exist (S3), F_a of both tsunami cases remain zero. However, when the lower structure (B) exists (S2), the tsunami reached the upper structure (A) and significant tsunami force acts on the upper structure (A). In the guideline (2012), the tsunami force acting on the upper structure due to the existence of the lower structure is not speculated. However, this tsunami force is not small enough to be neglected as shown in Fig.10 and so it should be taken into proper consideration for the design of piloti-type buildings.

Figure 10(b) shows the results of F_b. F_b of the piloti-type buildings (S2) are almost same as the normal building (S1). However, when the lower structure (B) locates farther from the front face of the upper structure (A) (L=1.0D, 2.0D, 4.0D), F_b is slightly larger than the normal building. Some photos presented in Fig.6 show a lot of air was being entrapped in front of the lower structure (B). It is suggested that velocity in front of the lower structure (B) was accelerated due to the lack of flow area by the entrapped air. This lack of flow area might have some influence on the tsunami force. However, the detailed reasons are not still sure and then further investigations are going to be conducted by the authors in the future.

According to the guideline (2012), the tsunami force acting on the lower structure of piloti-type building can be estimated by using the formulation for normal buildings. However, it was found that larger tsunami forces could act on a lower structure than a normal building. This issue should also be considered properly for the design of piloti-type buildings.

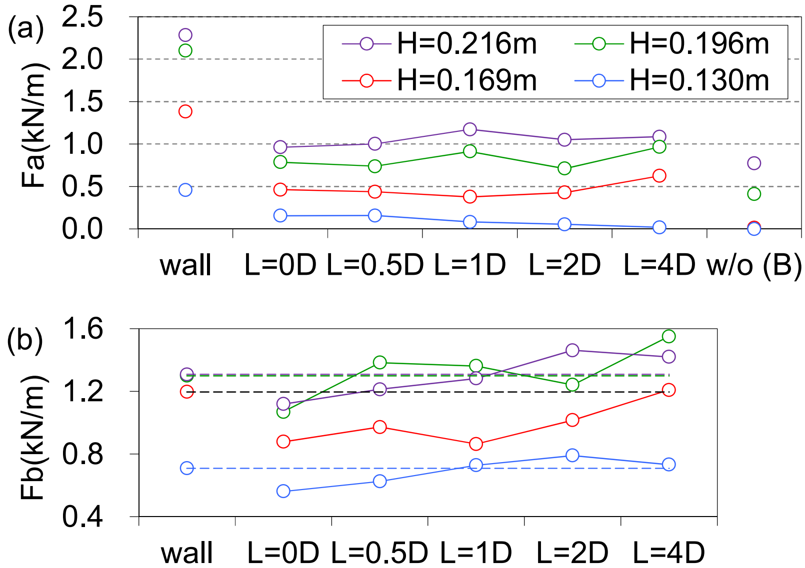


Figure 10. Horizontal tsunami forces acting on piloti building.

Maximum tsunami forces F_a in the case of S1, S2 (only L=0.0D) and S3 are plotted in Fig. 11. Here, horizontal axis means the maximum tsunami height without the structure normalized with the height of the ground floor. Two lines, which are defined in the guideline (2012), are described in this figure. The dot line should be applied to the normal building. Dash line should be applied to the piloti-type building. S1 data plotted by red circle should correspond to the dot line. Most S1 data are in good agreement with the dot line but there are some unfitted data. The unfitted data were obtained in the steeper wave case. In this case, splash of water was observed at the initial impact of the upper structure.

Then, the disagreement of these data with the dash line may be caused by complex water flow in front of the structure including splash and drop of water.

In the case of S3, when the tsunami height is lower than the ground floor height, $H_0/D < 1$, the tsunami force F_a does not act on the upper structure. When the tsunami height is higher than the ground floor height, $H_0/D > 1$, S3 data plotted by blue circle should correspond to the dash line. However, most measured data are plotted over the dash line. It means that the design tsunami force defined in the guideline for a piloti-type building will underestimate the actual tsunami force acting on the upper structure.

In the case of S2, even when the tsunami height is lower than the ground floor height, $H_0/D < 1$, the F_a significantly acts on the upper structure. This is due to the existence of the lower structure. Compared with the design tsunami forces in the guideline, S2 data are plotted between the two lines. It means that the design tsunami force for a normal building will overestimate but the design tsunami force for a piloti-type building will underestimate the actual tsunami force on the upper structure.

From these results, it was found that the design tsunami forces defined in the guideline do not able to estimate the actual tsunami forces on piloti-type buildings properly. At present, authors are taking efforts to improve the current design guideline for piloti-type buildings.

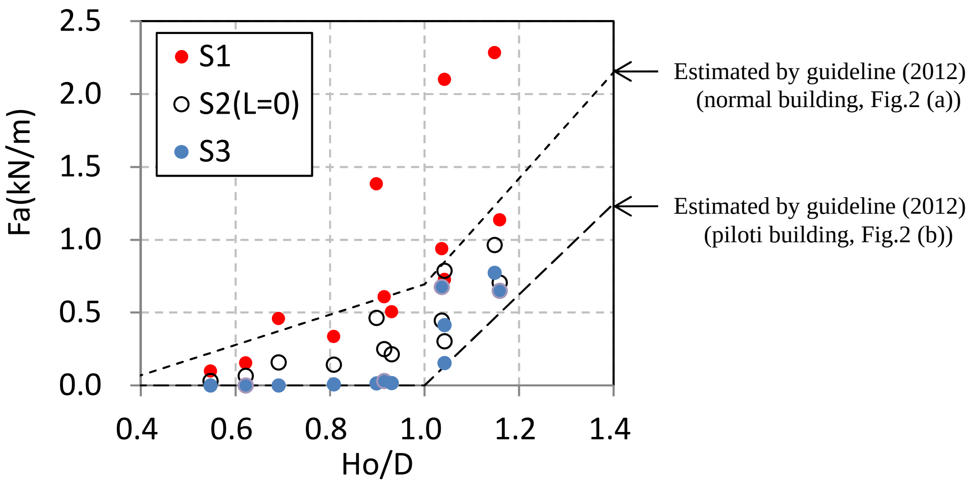


Figure 11. Tsunami force F_a acting on upper structure (A) compared with guideline (2012).

Uplift tsunami forces acting on ceiling of ground floor

Figure 12 shows the distribution of the uplift tsunami pressure acting on the ceiling in front of the lower structure, which were measured when the maximum uplift force F_s was recorded. In the case the lower structure locates farther from the front face of the structure (L=1.0D, 2.0D, 4.0D), the distribution of the uplift pressure is almost uniform. On the other hand, in the case the lower structure locates near the front face of the structure (L=0.5D), the uplift pressure is quite large and some of them exceed the capacity of the pressure gauge (set 10kPa in this experiments). It is known that the design force for a slab such as a celling of a building is defined as several kPa. The experiments revealed, however, that more than several hundred kPa could act on the celling in the real scale. Since the duration of this impact force is quite short, this impact force will not directly cause the destruction of a building. However, it will possibly damage the members of the piloti-type building. Although the reasons why this large pressure occurred are still under investigation, this issues is quite important to design more resistant piloti-type buildings.

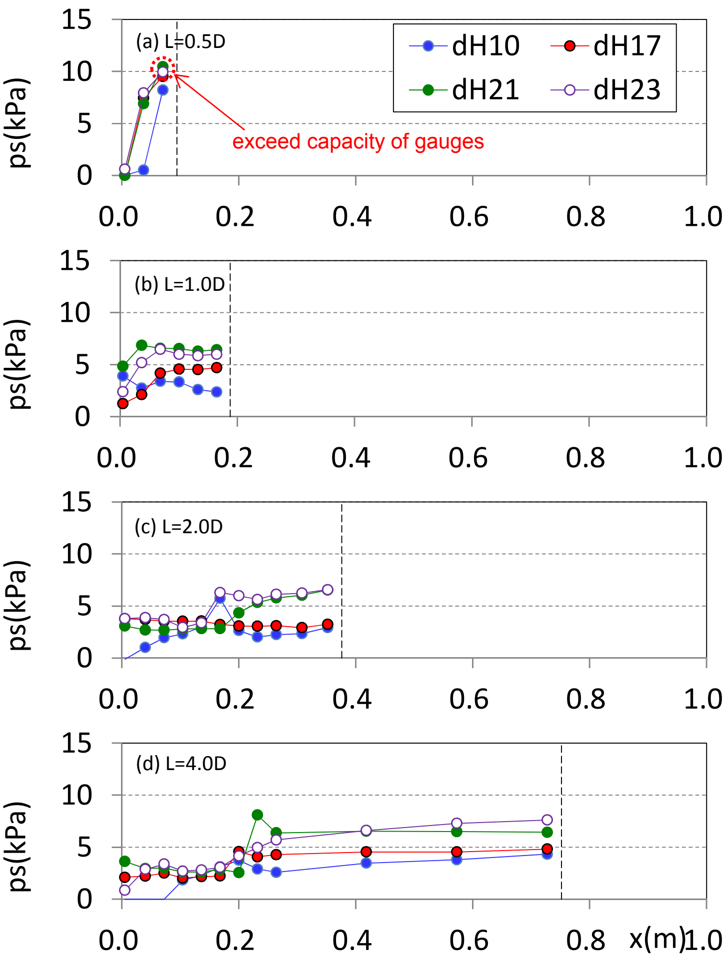


Figure 12. Uplift tsunami forces acting on the ceiling of the ground floor.

CONCLUSIONS

As a result of the physical model tests, the followings were obtained:

- When tsunami shape is milder, tsunami forces for normal buildings can be estimated by using the formulation in the guideline (2012). However, when tsunami shape is steeper, tsunami force tends to be larger than the design tsunami force for a normal building.
- When a building is piloti-type, tsunami force acting on an upper structure becomes significantly smaller compared with a normal building. However, the tsunami force tends to be larger than the design tsunami forces for piloti-type buildings.
- Even when tsunami height is lower than the celling of ground floor, significant tsunami force could act on the upper structure due to the existence of a lower structure.
- Uplift tsunami force acting on the ceiling in front of the lower structure could be much larger than the usual design force for the ceiling of the buildings.

These physical model tests were performed under the limited conditions in terms of the tsunami waves and the types of the structures. The tests should be continued under much wider conditions and more data should be collected. By collecting the more experimental data and doing further investigation, the authors will hopefully contribute to the better understanding mechanism of tsunami-piloti structure interactions and the further improvement of the current guideline for piloti-type buildings.

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