Evaluation of Tsunami Load and Building Damage Mechanism Observation in the 2011 off Pacific Coast of Tohoku Earthquake

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SUMMARY:
On-the-spot investigations at the Tohoku inundation area were conducted after the 2011 Tohoku Earthquake. A damaged two-story steel building located at Onagawa city was chosen to evaluate the tsunami-induced force. The results estimated that the tsunami load that acted on the outer wall of the building was over 24.0 kN/m^2 based on the evaluation of the ultimate design strength and the outer wall area of the building. In the Tsunami Evacuation Building Design Guideline, the tsunami load is assumed to follow a triangle distribution along the height. This distribution assumes the tsunami load as a hydrostatic force, but it was contradicted the observed failure pattern. Uniform distribution along the height, which assumes a hydrodynamic force, is found to better explain the failure mechanism.

Keywords: Tsunami, horizontal external force, maximum load, load distribution, building damage

1. INTRODUCTION

The 2011 Tohoku Earthquake, having a magnitude of 9.0, generated a tsunami that reached 23 m in height and caused damage to over 100,000 buildings, took at least 15,000 lives and 25 trillion yen lost (National Institute for Land and Infrastructure management, 2011, Architectural institute of Japan, 2011). The tsunami-induced coastal flooding led to extensive casualties and tremendous economic losses. The significantly large tsunami load raised public awareness since the 2004 Sumatra earthquake. It is indicated that existing design codes did not properly account for the large forces and impacts generated by tsunamis (Saatcioglu M. et al., 2006). The tsunami-induced forces caused severe damage or collapse of buildings. Experimental studies (Lukkunaprasit P. et al., 2009, Nouri Y. et al., 2010), tsunami resistance structure design guidelines (Tsunami Evacuation Building Guideline Committee, 2005, Federal Emergency Management Agency, 2008), and hydraulic model analysis (Asakura R. et al., 2002) conducted after the Sumatra earthquake have been referred to in the tsunami load evaluation. However, quantitative research about the tsunami load and corresponding building damage mechanisms is very limited.

An occurrence of another subduction zone earthquake having a magnitude over 8.0 is anticipated within fifty years, that would have a large impact in the Southwestern part of Japan (Kamae K. et al., 2004). The subduction zone is close to many large cities including Tokyo, Nagoya and Osaka. Therefore, there is a urgent need to accumulate quantitative data on the tsunami load and correspond building damage mechanisms.

In this study, on-the-spot investigations at the Rikuzentakada, Sendai, and Kesennuma cities in the Tohoku area were conducted one month after the earthquake. Damage patterns of buildings and corresponding locations, earthquake intensities, and tsunami height were recorded in detail. A damaged two-story steel building located at Onagawa city was chosen as the building for close simulation. Tsunami load was estimated based on the tsunami evacuation building design guideline. Comparing the ultimate design strength with the damage mechanism of the concerned building, the intensity of tsunami load and the load distribution that are stipulated in the design guideline were examined.

2. LOCATION AND DAMAGE PATTERN

On-the-spot investigations in Onagawa city (Figure 1) were conducted on April 14th and May 5th of 2011. Among the damaged buildings, wood houses sustained most serious damage. Most of them were washed away by the tsunami (Figure 2(a)). In many cases in steel buildings, curtain walls were destroyed, but the deformed steel frames remained (Figure 2(b)). Many reinforced concrete buildings survived, but some overturned cases were observed (Figure 2(c)). A variety of tsunami loads acting on different structure systems or different dimensions lead to different damage mechanisms.
To examine the tsunami load, a damaged two-story steel building was chosen as the building to look into. The building sustained an large shaking (MM10), and tsunami height reached 15 m.

Figure 1. Investigation area (Onagawa city of Miyaji province)

(a) Wood building foundation (b) Damaged steel building (c) Overturned RC building

Figure 2. Major damage patterns of buildings

3. THE OBSERVED BUILDING

The observed building was about 100 m from the Onagawa port (Figure 3). The transverse direction of the building was paralleled to the coast line. The south side of the building facing the Onagawa port was denoted as "sea side", and the north side was denoted as "land side".

The building was a steel moment frame with ALC panel curtain wall and RC floor slabs. The first and second stories were both 3.6 m in height. The structural plan of the building is shown in Figure 4. The longitudinal and transverse directions are 12.4 and 13.7 m in length, respectively. Braces were placed between column C1-C2, C3-C4, C5-C6 and C7-C8. Figure 5 shows an overview of the damaged building. No plastic deformation was observed at the first story. The second story sustained serious plastic deformation. Tsunami load acted on the south side of the building and caused the second story to significantly lean to the land side. Based on the strength of structural members, the longitudinal ultimate strength of the second story of the observed building was estimated to 493 kN. The longitudinal elastic limit strength and the ultimate strength of the first story were 1,418 kN and 1,699 kN, respectively.

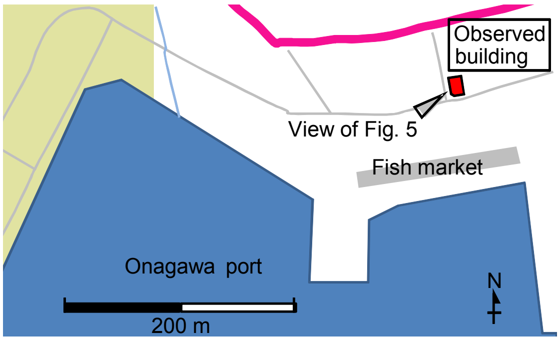

Figure 3. Location of observed building

Figure 5. Observed building

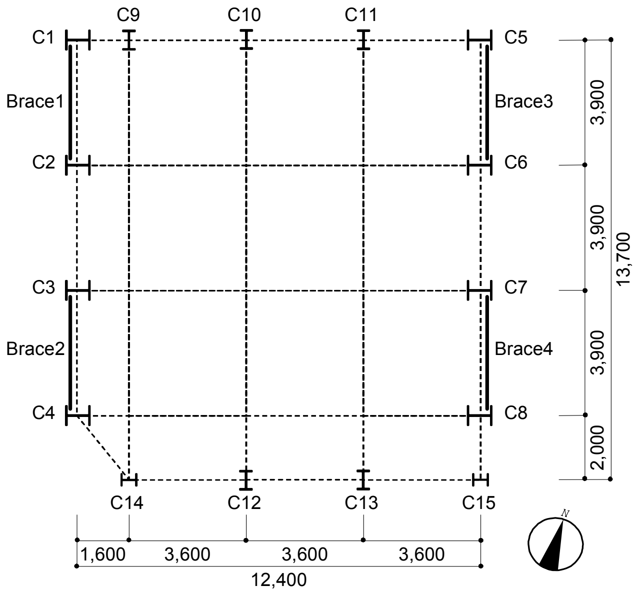

Figure 4. Plan of observed building (Unit: mm)

4. TSUNAMI FORCE EQUATION AND THE OBSERVED BUILDING STRENGTH

Tsunami Evacuation Building Design Guideline (Tsunami Evacuation Building Guideline Committee, 2005) is the only material available for tsunami resistance building design in Japan. The tsunami load estimation equation shown blow, is obtained based on the hydrostatic force distributed in an inverted triangle pattern along the height.

$$Q(z) = \rho g B \int_{z_1}^{z_2} (3h - z) dz = \frac{1}{2} \rho g B \left\{ \left(6hz_2 - z_2^{\,2}\right) - \left(6hz_1 - z_1^{\,2}\right) \right\} \quad (4.1)$$

Here, $Q(z)$ represents the tsunami force (kN), h is the design water height above the base of the wall at the structure location (m), B represents the breadth of the concerned area (m), z_1 is the minimum height of the compress area ($0 \leqq z_1 \leqq z_2$) (m), z_2 represents the maximum height of the compressed area ($z_1 \leqq z_2 \leqq 3h$) (m) and ρ represents the fluid density (t/m^3). The ultimate strength of the second story was 493 kN. According to the equation, when the tsunami force that acted on the roof of the second story reached the ultimate strength (493 kN), the distribution of the horizontal force per unit area can be determined by tuning the water height, $3h$. The estimated force distribution is shown in Figure 6. Here, ALC panels of the second and first stories were pin connected at the roof and the second story slab, the second story slab and the first story slab (ground elevation), respectively. The horizontal forces acting on each ALC panels were distributed on each of the upper and lower story beams. The exterior wall area of each story that sustain tsunami forces was 41.04m^2 (window openings considered). When the tsunami force that acted on the roof reached the ultimate strength (493 kN), the water height ($3h$) arrived at 8.45 m. The resultants that acted on the roof and second story slab were 1,951kN (734kN + 1,217kN) and 1,458 kN. The horizontal force that acted on the first story was 2,444kN (493kN + 734kN + 1,217kN) in total. This horizontal force exceeded the estimated resistances of the first story (the elastic limit strength and the ultimate strength was estimated at 1,418 kN and 1,699 kN). This contradicts the observed damage (the first story remained elastic and second story collapsed). The hydrostatic force distribution assumed in the estimation equations is responsible for the difference between observed and predicted behavior. To match the damage pattern of the observed building, the horizontal force acted on the second story slab had to be smaller than 1,951 kN. When the uniformly distributed hydrodynamic force is considered, the obtained force would become closer to the building collapse mode.

5. HYDRODYNAMIC FORCE AND DAMAGE PATTERN

When the tsunami force is considered to be uniformly distributed along the height, the force acted on the ALC panels can be distributed equally to the upper and lower story beams. The hydrodynamic force acting on the roof, the second story slab, and the first story slab of the observed building would have a ratio of 1:2:1. Then, the ratio of the first story horizontal resultant force to the second story horizontal resultant forces is 3:1. The ratio of the second story force to the first story force is 0.333.

For the observed building, the ratio of the second story ultimate strength to the first story elastic limit strength was 0.348. The horizontal external force ratio was close to the horizontal resistance ratio of the building. When the first story exceeded the elastic limit, the second story would reach the ultimate stage. This matched the observed damage pattern; the first story remained elastic and the second story was close to collapse. The uniformly distributed hydrodynamic force was deemed more reasonable for the tsunami load estimation of the observed building.

When uniformly distributed hydrodynamic force is considered, the tsunami-induced horizontal force per unit area is obtained by the following equation.

$$F = \frac{{}_2S_u}{0.5A_{av}} \tag{5.1}$$

Here, A_{av} is the building exterior wall area of each story, which represents the area that sustaining tsunami. ${}_2S_u$ is the ultimate strength of each story of the building. For the longitudinal ultimate strength of the second story (493 kN), the tsunami load F was 24.0 kN/m^2. The relationship of tsunami load and inner force distribution are shown in Figure 7. The horizontal force acting on the exterior walls of each story are 986 kN in total. 493 kN is distributed to each of the upper and lower story beams. With these assumptions, when the second story reaches the ultimate strength, the first story still remains elastic, which matches the observed failure mode.

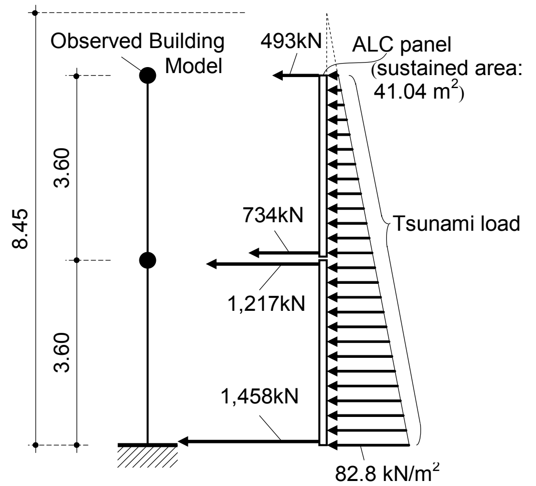

Figure 6. Tsunami load distribution

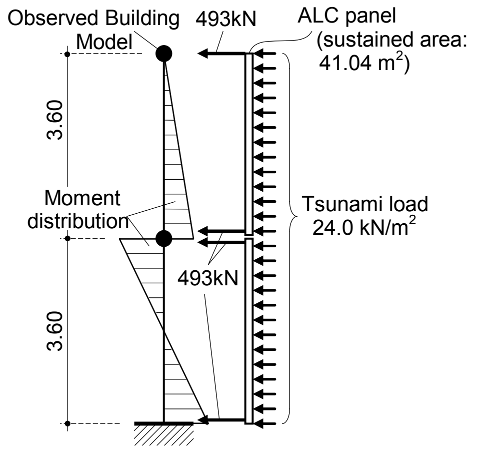

Figure 7. Tsunami load acted on the building

6. TSUNAMI LOAD ON SMALL BUILDING

The tsunami estimation equations in the Tsunami Evacuation Building Design Guideline (Tsunami Evacuation Building Guideline Committee, 2005) was established based on the hydrostatic force. The triangle distribution of the hydrostatic force is achieved due to a different water depth at the opposite side of the structure. For large structures such as embankments, the tsunami would need more time to flow and fill in on all sides of the structure and could caused a difference in water depth of 10 m at a certain instant. However, for a small building, the wave would quickly flow to the back side of the structure. In such a condition, the water depth difference is not likely to exceed 5 m.

In tsunami estimation equations, the water depth difference at the opposite side of the structure should be considered based on the dimension of the structure. However, in the Tsunami Building Design Guideline (Tsunami Evacuation Building Guideline Committee, 2005), the tsunami load is estimated by hydrostatic force regardless to the dimension of structure. When the tsunami runup exceeds 10 m such as the case in Onagawa city, the tsunami load estimation for small building such as the observed building may cause a significant overestimation. However, the hydrodynamic force that may distribute uniformly along the height is not considered in the guideline. The results obtained from the equation failed to explain the damage pattern of the observed building.

7. CONCLUSIONS

On-the-spot investigations at Rikuzentakada, Sendai, and Kesennuma cities in the Tohoku area were conducted after the 2011 Tohoku Earthquake. A two-story building located in Onagawa city was chosen to examine the tsunami load and corresponding damage. Major observations obtained from this study are summarized as follows:

1. The tsunami load that acted on the outer wall of the observed building was estimated to be over 24.0 kN/m^2 based on the evaluation of the ultimate design strength and the outer wall area of the building.

2. In the Japanese Tsunami Evacuation Building Design Guideline, the tsunami load is assumed to follow a triangle distribution along the height. The distribution assumes the tsunami load as a hydrostatic force, but it contradicted the observed failure pattern. Uniform distribution along the height, which assumes a hydrodynamic force, is found to better explain the failure mechanism.

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