DAMAGE DUE TO TSUNAMI AND TSUNAMI RESISTANCE PERFORMANCE OF WOOD HOUSES DURING THE GREAT TOHOKU EARTHQUAKE

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SUMMARY:
Japan has been suffered much damage due to earthquake. The 2011 off the Pacific coast of Tohoku Earthquake (the Great East Japan Earthquake) occurred last year. The field surveys of the damage on wood buildings were conducted many times just after the earthquake. Damage on wood buildings due to tsunami was extremely heavy. However, there were many wood houses remained against the tsunami. The structural specifications und flood water depths of the remained houses were investigated. As a result, the relationships between the flood water depth and damage, the construction methods and the resistance performance against tsunami were clarified.

Keywords: Wave force, Lateral load, Inundation direction, Opening, Wash away

1. INTRODUCTION

A lot of wood buildings suffered crushing damage due to tsunami caused by the Great East Japan Earthquake. The flooded area by the tsunami extended to Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba prefecture[1)]. However, there were not few wood houses to remain in by this tsunami. When the disaster stricken area will be recovered and National Institute for Land and Infrastructure Management (NILIM), MLIT and Building Research Institute (BRI) performed field survey[2)] for the purpose of getting fundamental information to discuss how the residential building should be constructed in the tsunami hazard area. In this paper, a summary of the survey results and an examination result of relations of tsunami wave force and lateral resistance performance of wood buildings were reported.

2. FIELD SURVEY

2.1. Outline of field survey

The field surveys were conducted to grasp the damage to the wood buildings due to tsunami and the characteristics or conditions of the building washed away and remained. The field surveys were carried out both in plain area and slope land. The surveyed area and schedule were shown in Figure 2.1 and Table 2.1, respectively. In the surveyed city and town, we didn’t survey all the area of the city and town exhaustively, and surveyed only a part of the flooded area selectively due to limitations of time and human resources. Therefore, what is mentioned in the followings is the knowledge which was provided in the surveyed area at the surveyed time.

2.2. Damage in plain area

There were few things to block tsunami in plain area, many wood buildings suffered crushing damage due to tsunami. The flood water depth in the surveyed area estimated by the flooded water trace on the building wall was shown Table 2.2.

Table 2.1. Survey schedule

Category	Cities and towns	Date
Plain area	Wakabayashi ward in Sendai city, Natori city, Iwanuma city, Watari town, and Ymamoto town in Miyagi prefecture	April 6-8, 2011.
Slope land	Ohtsuchi town, Kamaishi city, Ohfunato city, and Rikuzen-takada city in Iwate pref., Kesen-numa city, Minami-Sanriku town, Onagawa town, Higashi-Matsu-shima town in Miyagi pref.	May 25-27, 2011.

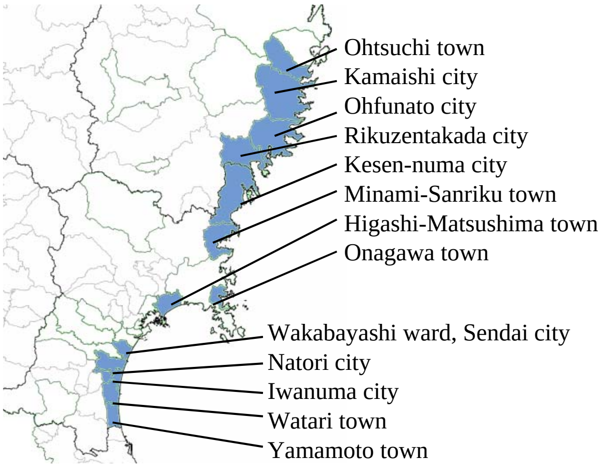

Figure 2.1. Locations of surveyed area

Table 2.2. Estimated flood water depth

Surveyed area	Estimated flood water depth
Arahama, Sendai	6-8
Arahama-shin, Sendai	5-6
Yuriage, Natori	5-6
North of Arahama port, Watari	6
West of Arahama port, Watari	4

2.2.1. Wood houses washed away

In the area with over 5 m flood water depth, most of the wood houses in the inundated area were washed away by the tsunami. How the houses were washed away; as for the case which the whole house including foundations was washed away (Photo 2.1), the case which only foundations were left (Photo 2.2), the case which sills and foundations were left (Photo 2.3), the case which sills, foundations and floor boards were left (Photo 2.4), and so on, were observed. There were several cases that the hold down fastener was failed, as shown in Photo 2.5. The foundations or wall of bath room made by concrete block often remained in, as shown in Photo 2.

2.2.2. Wood buildings remained

Most of wood houses near the shore in the area of Arahama, Arahama-shin, and Yuriage were washed away. However, not all the houses were washed away. For example, many houses which were located far from the shore remained (Photo 2.6). The houses in the downstream of RC building remained, as shown in Photo 2.7. A group of houses that remained downstream of large RC apartment building as shown in Photo 2.8. The buildings that survived were a mix of older and newly constructed wooden houses. In addition, the factory building protected wood houses for an even further distance. This is expected to be due to the relatively new construction of these houses that had better structural specifications, as shown in Photo 2.9.

Photo 2.1. Foundations washed away.

Photo 2.2. Only foundation remained.

Photo 2.3. Foundations and sills remained.

Photo 2.4. Sills, foundations and floor boards remained.

Photo 2.5. Failed hold down fastener.

A line of wood houses remained were confirmed in Arahama-shin, Wakabayashi ward, Sendai city, as shown in Photo 8. The front survived house of the line was non-wooden. The flood water depth in this area was estimated at the level about 4-5 m. On the other hand, wood house which didn't have survived buildings in the inundation direction avoid being washed away, but suffered heavy damage, as shown in Photo 2.11. Several such houses were confirmed in each surveyed area and were built by the better specification, for example, with many metal fasteners.

It was often confirmed that the hybrid construction building with RC and timber construction, as shown in Photo 2.12 were remained. This building consisted of RC structure for the 1st floor and wood construction on the 2nd floor. Photo 2.13 shows a 1-story glulam framed structure in which the wood structural members remained intact, but the building was filled with floating wreckage and building materials.

A 3-story wood house was remained, as shown in Photo 2.14, in the heavily damaged area with very few houses remaining under about 6 m flood water depth. It might be the reason why the lateral strength of 3-story house was larger than that of 2-story house.

Photo 2.6. Many wood houses remained.

Photo 2.7. Wood house to remain in the downstream of RC building in Arahama, Sendai city.

(a) Conspectus on the ground

(b) Aerial photograph

Photo 2.8. Group of wood houses that escaped damage downstream of large RC structure

(a) Conspectus on the ground (b) Aerial photograph

Photo 2.9. Wood houses remained in the downstream far from the survived factory building.

(c) Conspectus on the ground (d) Aerial photograph

Photo 2.10. Wood houses to remain in the shape of a line in Arahama-shin, Wakabayashi ward, Sendai city.

Photo 2.11. Remained house which didn't have survived buildings in the inundation direction.

Photo 2.12. The remained hybrid construction consisting of RC for the 1st floor and wood construction on the 2nd floor.

Photo 2.13. Remained glulam frame structure.

Photo 2.14. Remained 3-story wood house.

2.2.3. Relationships between damage and flood water depth

For example, Arahama district in Watari town is surrounded with sea shore and faces the Pacific Ocean in the east, and there is a port in the south side, as shown in Figure 2.2. In the area between Pacific Ocean and Arahama port, most of wood houses were washed away. In the north area of the Arahama port, the flood water depth was estimated to be about 6 m. Many of wood houses were washed away. On the other hand, in the west area of the Arahama port, the flood water depth was estimated to be about 4 m. Many of wood houses remained.

2.3. Damage in slope land

The damage in Akasaki-cho, Oofunato city was reported as an example of the tsunami damage in several surveyed slope lands. Akasaki-cho is located in the east of Oofunato bay, and is a gradual slope land. Similar to plain areas, many of wood houses were washed away by tsunami here in Oofunato. The wood house (Photo 2.15) located just near the shore where the height of the tsunami reached to the top of 2nd story (about 7 m high), and went under the flood water completely. The house was damaged in a part, but wasn't washes away. The next work shed whose sill came off from floor concrete moved. On the other hand, the 2-story wood house (Photo 2.16) just near them suffered almost no damage. Two houses next to them remained, but there is a hill behind the two houses. Therefore, the hill behind the building may make the tsunami wave force lower.

Figure 2.2. Aerial photograph and the flood water depth estimated in Arahama, Watari town.

Photo 2.15. Wood house remained under the flood water depth of over 7 m.

Photo 2.16. Wood house without damage under the flood water depth of over 7 m.

Photo 2.17. Survived house which might have comparatively slight structural specifications.

Photo 2.18. Survived soil warehouse which might have comparatively slight structural specifications.

Photo 2.19. Survived old house which rotated and moved horizontally

At the location where we went up the slope land from the shore, a light steel-frame house remained under the about 5 m flood water depth which was estimated by the water trace on the wall of the house. In the next of this house, the 1-story old wood house (Photo 2.17) whose structural specification was not so good, but the anchor bolts were installed remained. In addition, a warehouse with mud walls (Photo 2.18) was remained and an old wood house without anchors (Photo 2.19) turned and moved horizontally. Because the wood house under about 5 m flood water depth were almost washed away in plain areas, it might be possible for the slope land to make the tsunami wave force a little lower.

3. RELATIONSHIP BETWEEN TSUNAMI WAVE FORCE AND LATERAL STRENGTH OF WOOD HOUSE

After the damage due to the Indian Ocean tsunami in 2004, the Cabinet office published the Guidelines for Tsunami Evacuation Buildings[3)] in June 2005. This document is meant to promote the spread of tsunami evacuation buildings in areas that are difficult to escape from tsunami waters. Specifications and other precautions were prepared for the structural requirements of the tsunami evacuation buildings.

3.1. Calculation of the tsunami wave pressure

The tsunami wave pressure in the inundation direction is assumed to act with the triangular wave distribution shown in Figure 3.1. Tsunami wave pressure distribution for structural design was three times the normal design water height in the hydrostatic pressure distribution in the guideline. Here, 3 is the coefficient of water depth proposed by the waterway model test[4)]. The wave pressure in the inundation direction is calculated by the following equation[3)].

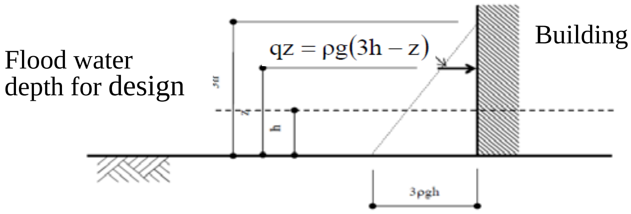

Figure 3.1. Calculation formula of wave pressure

$$q_z = \rho g\,(3h - z) \tag{3.1}$$

Where, q_z : Wave pressure in the inundation direction (kN/m^2)
ρ : Density of water (kg/m3)
g : Acceleration due to gravity(m/s2)
h : Flood water depth for design (m)
z : Height above ground level of the portion ($0 \le z \le 3h$) (m)

3.2. Tsunami wave force calculation

The following equation is obtained by integrating the value of the pressure on the area receiving the wave pressure from the tsunami.

$$Q_Z = B\int_{Z_1}^{Z_2} q_Z dz = \rho g B\int_{Z_1}^{Z_2} (3h - z)dz \tag{3.2}$$

Where, Q_z : Tsunami wave force for structural design (kN)
B : Width of wall portion (m)
g : Acceleration due to gravity(m/s^2)
z_1 : Minimum height of pressure receiving surface ($0 \le z_1 \le z_2$) (m)
z_2 : Maximum height of pressure receiving surface ($z_1 \le z_2 \le 3\,h$) (m)

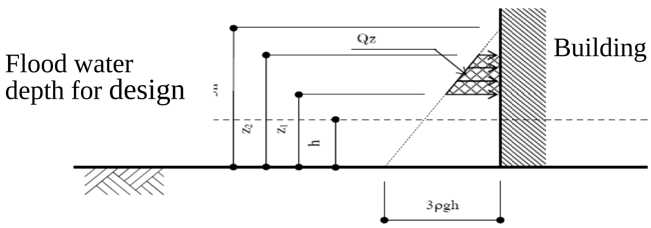

Figure 3.2. Calculation of wave force

3.3. Comparison with lateral resistance of timber building

To study the coefficient, assumed as 3 in the previous paragraph, of flood water depth, the relationships between the tsunami wave force and the lateral resistance of timber buildings were discussed. The structural details and the flood water depth of about 50 buildings which were chosen as objects of study were grasped and measured. All the buildings chosen were detached residential buildings including 1-story or 2-story and less than about 1km from the shore. Many of studied house were Japanese conventional post and beam construction, and some of them were light frame construction. The investigated houses were various in the degree of damage, as shown in Table 3.1. The distance from shore and the flood water depth of the houses to study were shown in Figure 3.3.

Table 3.1. The degree of damage on investigated houses

Degree of damage	State
Slight damage	There was no damage on structural members, but openings were failed.
Serious damage	Several columns were broken.
Remaining	It was remained, but degree of damage were unknown.
Washed away	It was washed away, but the flood water depth could be able to be estimated by the next building or electrical pole.

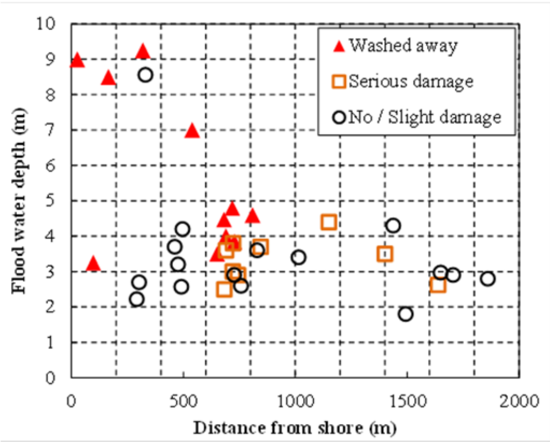

Figure 3.3. The distance from shore and the flood water depth of the houses investigated.

Assuming that the openings of the houses don't break, the tsunami wave force of each house was integrated from the top of base to the flood water depth or height of building by the Eqs. 3.3 depending on the shapes of the elevation.

$$Q_z = B \int_{z_1}^{z_2} q_z dz = \rho g \, B \int_{z_b}^{z_w} (\alpha h_w - z) \, dz \quad (3.3)$$

Where, Q_z : Tsunami wave force for structural design (kN)

α : Coefficient of flood water depth

h_w : Measured flood water depth (m)

z_b : Height of the base (m)

z_w : The lower value of height of the building or maximum height of pressure receiving surface ($z_b \leq z_w \leq 3\, h_w$) (m)

Next, the lateral shear strength of each house was calculated by reading the structural elements from the design documents. The lateral shear strength was determined as 1.5 times the allowable tolerance of each structural element. The coefficient α which the wave force and the shear strength were just equal in was calculated. Therefore, the calculated coefficient α of the house washed away is smaller than that to use in the structural design. And, the calculated α of the remained house is larger than that to use for the structural design.

The relationship between the flood water depth and the coefficient α were shown in Figure 3.4. The deeper the flood water is, the smaller the coefficient α is. It is clarified that the house under the much flood water depth was acted by the relatively small wave force. And, the coefficients α were not over 2.0, and most of them were in the range from 1.0 to 2.0. On the other hand, the relationship between the distance from the shore and the coefficient α were shown in Figure 3.5. The both of them were not in significant correlations. However, these are the results that studied only lateral shear strength against the tsunami wave force. To resist the tsunami, wood houses must have performances of the sliding and the rocking of whole house, the floating, the shear force to the anchor bolts, the members resisting to the water pressure. Therefore, these studies are not complete.

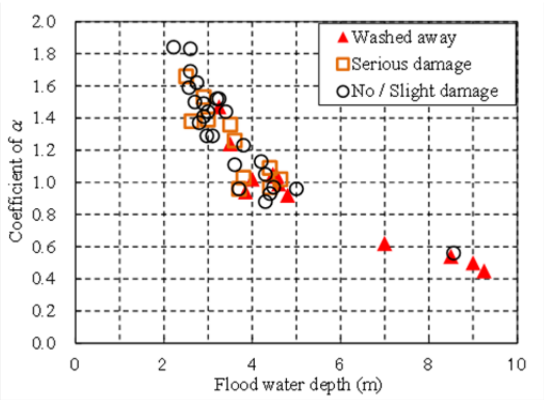

Figure 3.4. The distance from shore and the flood water depth of the houses investigated.

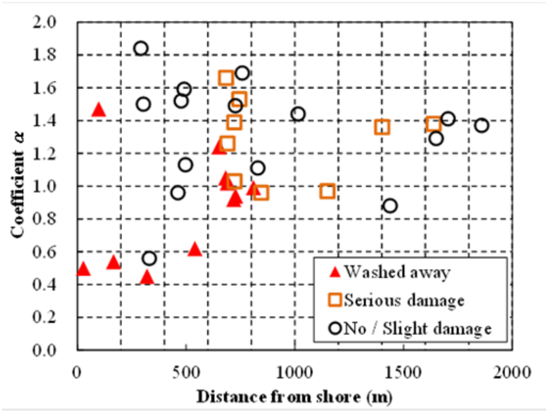

Figure 3.5. The distance from shore and the flood water depth of the houses investigated.

4. CONCLUSION

Results of field surveys were summarized as follows;
1) All of the low-rise wood houses were not washed away by the tsunami. 2) In the downstream of survived buildings more than a middle-rise, many wood houses remained. 3) In the downstream of survived low-rise buildings, or at the location far from survived middle-rise buildings, only the wood houses with excellent structural specification remained. 4) Some wood houses remained alone without survived buildings in the inundation direction. In that case, there were many examples that some columns or walls were carried away in the inundation direction. 5) Having metal fastener or not in the column end joints such as the hold down fastener doesn’t decide whether the house is washed away or remained. 6) Glulam frame building, Hybrid structure consisting of RC for the 1st story and wood construction on the 2nd story, and 3-story house were often remained. 7) It was possible for the slope land to make the tsunami wave force a little lower.

Results of studies on structural performance and tsunami wave force were summarized as follows;
1) The deeper the flood water is, the smaller the coefficient of water depth α is. 2) The coefficients of water depth α were in the range from 1.0 to 2.0, approximately. 3) The coefficients of water depth α don’t relate to the distance from the shore.

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