7. Damage to Buildings in Inundation Areas Induced by Tsunami

7.1 Introduction

The purpose of this investigation is to understand an overview of buildings damaged by tsunami, in order to obtain basic data and information required to evaluate mechanisms for causing damage to the buildings and to contribute to tsunami load and tsunami-resistant designs for buildings such as tsunami evacuation buildings. The investigation was conducted by collecting building damage cases caused by tsunami, classifying the damage patterns for different structural categories, and making a comparison between the calculated tsunami force acting on buildings and the strength of the buildings.

The tsunami damage survey team* organized in the Joint Survey Team consists of 27 members, for voluntary investigation. The team collected national and international standards and codes concerning tsunami evacuation buildings and tsunami loads and surveyed about 100 buildings and structures in three site investigations.

7.2 Classification and Discussion of Damage Patterns

7.2.1 Reinforced concrete buildings

1) Collapse of first floor

A case that column capitals and bases on the first floor in a building were subject to bending failure and subsequently to story collapse was seen in a 2-story building (Photo 7.2-1).

The building had column-to-beam frames. The first floor had relatively small number of walls, but many concrete block walls were placed on the second floor. The first and second floors of the building in Photo 7.2-1 were used as shop and dwelling, respectively. The relevant building was estimated to have structural characteristics of low strength and stiffness on the first floor. As an opening on the second floor was not large, it is assumed that the second floor suffered a large tsunami wave pressure and the shear force acting on the first floor exceeded the lateral load-bearing capacity, resulting in the collapse of the building. Story collapse of the first floor has not been observed in 3-story or higher buildings in the investigations. In 3-story buildings, in general, reinforced concrete walls are often used in the first floor. Therefore, the strength of the first floor of 3-story buildings is considered to have been larger than that of 2-story buildings.

Photo 7.2-1 Story collapse of a 2-story reinforced concreted building

2) Overturning

Overturning was observed in 4-story or lower buildings. In all overturned buildings, the maximum inundation depth exceeded their height. Overturning types include buildings that fell sidelong (Photo 7.2-2) and buildings that turned upside down. Most of the overturned buildings were of mat foundation. In some overturned buildings on pile foundation, piles were pulled out.

Photo 7.2-2 Overturning of a 3-story reinforced concrete building

Overturning cases were often seen in 4-story or lower buildings with relatively small size of openings. However, there were many cases that 4-story or lower buildings with large size of openings were not overturned. Consequently, the size of opening on an exterior wall is considered to have greatly affected overturning.

In some cases, there were tsunami traces at the heights of the upper end of openings on the top floor inside the buildings whose heights were exceeded by maximum inundation depths. It is considered that air has accumulated in the space between the ceiling and the upper end of openings. Overturning is considered to occur when an overturning moment by tsunami wave force exceeds an overturning strength by a dead load of a building (considering the effect of buoyancy as required). A building, in which the distance from the upper end of an opening on each floor to a ceiling is long, may be overturned even by a slight horizontal tsunami force when buoyancy significantly acts on the building.

3) Movement and washout

Most of the overturned buildings were moved from their original positions. It is estimated that large buoyancy acted on the buildings. Moved and overturned buildings left no dragged traces on the ground. One of the buildings moved over a concrete block fence that had about 2m height on an adjoining land without destroying the fence (Photo 7.2-3). The building seems to have floated up by buoyancy. Some of the 2-story apartment houses with the same shape that were overturned were washed away and missing. A buoyancy and large horizontal force seem to have acted on these buildings.

Photo 7.2-3 A 2-story reinforced concrete building that moved over the fence and overturned

4) Tilting by scouring

When tsunami acted on a building, a strong stream was generated around the corner of the building, resulting in many large holes on the ground that were bored by scouring. In one case, a building on mat foundation fell into a hole bored by scouring (Photo 7.2-4).

Photo 7.2-4 A 2-story reinforced concrete building that was tilted by scouring

5) Fracture of wall (fracture of opening)

When tsunami acts on openings in a building and openings of the opposite side of the building are smaller than the affected openings, a stream flowing from the affected openings concentrates on the opposite small openings. In one observed case related to this event, a stream generated by tsunami provided a large pressure to a reinforced concrete non-structural wall around small opposite openings. The pressure enlarged the concrete wall to the outside and fractured the wall reinforcement. A tsunami wave force that acts on a building will be reduced if the size of opening affected by the force becomes larger. The same trend is considered to apply to an outlet surface of the stream.

Cases that such wall reinforcement was fractured were often seen in wall members with single layer bar arrangement. In one damaged building (Photo 7.2-5), a 300 mm-thick shear wall with double layer bar arrangement and a support span of more than 10 m and without the second and third floor slabs was bent inside by tsunami wave pressure. However, a shear wall in an area (Photo 7.2-5 Back of the building, right-hand side), where there was a floor on the second story and a support span was not long in the same building, was not bent.

Photo 7.2-5 Out-of-plane fracture of reinforced concrete shear wall without floor

6) Debris impact

Debris impact was seen in most of the non-structural members such as window and ceiling materials. The number of cases of clear damage to skeletons was not large, but in one observed case, a multi-story wall in an apartment house was probably bored by debris impact (Photo 7.2-6).

Photo 7.2-6 Wall opening probably generated by debris impact

7.2.2 Steel buildings

1) Movement and washout by fracture of exposed column base

A typical case of building movement and washout was that a building moved and flew due to the fracture of anchor bolts and/or base plates at steel exposed column bases and the fracture of a weld between the column and the base plate (Photo 7.2-7). In most cases, foundation and some column bases were left in the site, but the upper structure of the building was moved beyond the site or missing.

Photo 7.2-7 Steel building overturned by fracture of column base anchor bolts

2) Movement and washout by fracture of capital connection

In damage cases relatively often seen that a capital connection on the first or second floor in a building was fractured, then the building was moved and washed away. When a column base has a large strength like concrete encases type or embedded type, this type of fracture is considered to occur. In one case (Photo 7.2-8), foundation in a building, and several columns on the first floor (or up to the second floor) were left on the site, and the columns fell in the same direction.

In most cases, welds between diaphragms with lower flanges and the first-floor columns were fractured and the sections of the columns were exposed. In one building, flanges of the second-floor H-shaped beams were torn. Based on the deformation states near the column bases, it is estimated that a tensile force acted on the first-floor columns, and then the first-floor capital connections were fractured after the first floor was greatly tilted to the same extent as the inclination of the remaining columns.

Photo 7.2-8 First-floor columns falling in the same direction

3) Overturning

One case that a whole building including foundation was overturned, was confirmed. Most of the AAC panels of claddings were left (Photo 7.2-9).

Photo 7.2-9 Overturning of a 3-story steel building

4) Collapse

Skeleton collapse including story collapse of the first floor was seen in a 2-story steel building (Photo 7.2-10). Partial collapse of a warehouse was also seen on the coast.

Photo 7.2-10 Story collapse of first floor in a 2-story steel building

5) Large residual deformation

Slight tilting was often observed with remaining their skeletons in steel buildings. In one case (Photo 7.2-11), a gabled roof frame building did not collapsed despite large residual deformation.

Photo 7.2-11 Tilted gabled roof frame

6) Full fracture and washout of cladding and internal finishing materials

Cladding materials such as AAC panel were almost fully fractured and washed away, and then a steel frame as a skeleton was remaining. This case was often observed (Photo 7.2-12). It is considered that an external force that acted on the skeleton became small due to early washout of the cladding materials. In the remaining building, slight tilting of the skeleton, member deformation on the face affected by tsunami, and members locally damaged possibly by debris impact, were observed.

Photo 7.2-12 A remaining 3-story steel building

In another damage case, openings on the face affected by tsunami and on its opposite face, or transverse faces were severely damaged and fractured possibly due to stream runoff.

7.3 Database for Investigated Buildings

Outer dimensions of about 100 buildings and dimensions of their skeletons were measured in the site investigation. Maximum inundation depths were measured from tsunami traces on surveyed buildings and surrounding buildings. These measurement results were integrated into a database for investigated buildings. Building name, address, building use, construction year, designation as tsunami evacuation building, structure category, number of stories, outer dimension, distance from seacoast (river), GPS position, altitude, surrounding circumstances, damage situations, etc., were recorded in the database. In addition, photos of investigated buildings that were taken from four directions as possible were attached to the database. Based on the database, the joint survey team estimated strengths of the buildings and tsunami loads on them, and is evaluating whether the estimated values are consistent with the damage situations.

7.4 Damage to Wood Buildings

7.4.1 Objectives of damage survey

Many of wood buildings built in the Pacific coast of Tohoku region were washed away by the tsunami caused by the 2011 Tohoku Earthquake. However, there were not few wood houses that remained in tsunami affected areas. The field surveys were conducted to grasp the outline of the damage to the wood buildings due to tsunami and the characteristics or conditions of the building washed away and remained.

7.4.2 Outline of survey

The field surveys were carried out both in plain area and slope land. The surveyed area and survey schedule were shown in Fig. 7.4-1 and Table 7.4-1, respectively. However, 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 inundated area selectively. Therefore, what are mentioned in the followings are the knowledge which was provided in the surveyed area at the surveyed time.

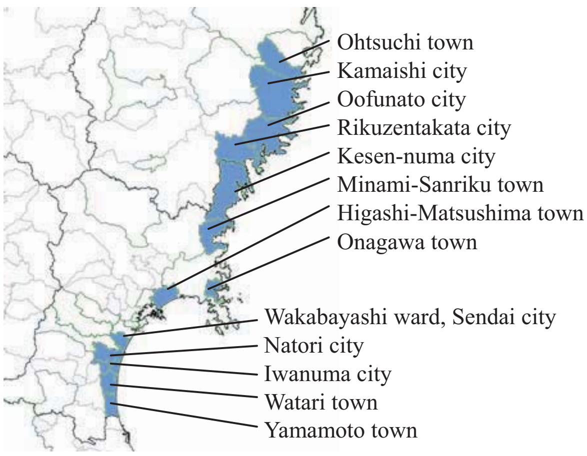

Fig. 7.4-1. Locations of surveyed area

Table 7.4-1. Survey schedule

Category	Surveyed cities and towns	Date of survey
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, Oofunato city, and Rikuzen-takata city in Iwate pref., Kesen-numa city, Minami-Sanriku town, Onagawa town, Higashi-Matsushima town in Miyagi pref.	May 25-27, 2011.

7.4.3 Damage in Plain Area

There were few things to block tsunami in plain area, a lot of wood buildings suffered crushing damage due to tsunami caused by the 2011 off the Pacific coast Thohoku Earthquake. The water depth in the surveyed area estimated by the water trace on the building wall was shown Table 7.4-2.

(1) Damage to wood houses

In the area with over 5 m 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 7.4-1), the case which only foundations were left (Photo 7.4-2), the case which sills and foundations were left (Photo 7.4-3), the case which sills, foundations and floor boards were left (Photo 7.4-4), and so on, were observed. There were several cases that the hold down fastener was failed, as shown in Photo 7.4-5. The foundations or wall of bath room made by concrete block often remained, as shown in Photo 7.4-2.

(2) Wood buildings remained in Arahama and Arahama-shin, Wakabayashi ward, Sendai city

Most of wood houses near the shore were washed away. However, not all the houses were washed away. For example, many houses which were located far from the shore remained, as shown in Photo 7.4-6. The houses in the downstream of RC building remained, as shown in Photo 7.4-7.

A line of wood houses remained were confirmed in Arahama-shin, Wakabayashi ward, Sendai city, as shown in Photo 7.4-8. The front survived house of the line was non-wooden. The water depth in this area was estimated at the level about 4-5 m. On the other hand, some wood houses which didn't have survived buildings in the direction where the tsunami came remained, but suffered heavy damage, as shown in Photo 7.4-9. Several such houses were confirmed in each surveyed area, and they were built by the construction methods with many metal fasteners.

Table 7.4-2. Estimated water depth

Surveyed area	Estimated water depth (m)
Arahama, Wakabayashi ward, Sendai city	6-8
Arahama-shin, Wakabayashi ward, Sendai city	5-6
Yuriage, Natori	5-6
North of Arahama port, Watari town	6
West of Arahama port, Watari town	4

Photo.7.4-1. Foundations washed away.

Photo.7.4-2. Only foundation remained.

Photo.7.4-3. Foundation and sills remsined.

Photo.7.4-4. Sills, foundation and floor boards remained.

Photo.7.4-5. Failed hold down fastener.

Photo.7.4-6. Many wood houses remained.

Photo.7.4-7. Wood house remained in the downstream of RC building in Arahama, Wakabayashi ward, Sendai city.

Photo 7.4-8. A line of wood houses remained
in Arahama-shin, Wakabayashi ward, Sendai city.

Photo 7.4-9. Remained house which didn't have survived buildings
in the direction where the tsunami came in Arahama-shin, Wakabayashi ward, Sendai city.

(3) Remained wood buildings in Yuriage, Natori city

Wood buildings also suffered crushing damage due to tsunami, as shown in Fig. 7.4-2. The parts of buildings remained, for example foundation, sill, and so on, were as same as mentioned in (1). Figures in rectangles in Fig. 7.4-2 show the locations of buildings mentioned in the followings. The wood house (Photo 7.4-10:1) united with the foundation and carried away. In the original position of it, steel tube piles remained as shown in Photo 7.4-11(2). Because a temple building (Photo 7.4-12:3) and a steel-frame house (4) were damaged heavily and remained, tsunami wave force was reduced to some extent, and the neighboring wood house with store avoided being carried away, as shown in Photo 7.4-13 (5). It might be possible for the survived low-rise building to make wave force reduce.

In the south east of Hiroura bridge (6), there was protect forest (Photo 7.4-14:7) of the pine trees with about 20 cm diameter at breast-height. The water depth was estimated to be about 5-6 m by the flotsam attaching to trees. A part of this protect forest fell down completely, in the downstream of this, the wood house (Photo 7.4-15:8) was washed away. On the other hand, in the downstream of survived protect forest, wood houses were selectively carried away and an example of the remained house was shown in Photo 7.4.16 (9). It seems to be generally thought that protect forest reduces wave force. However, because it cannot be thought that the strength of trees falling down continually was quite different by their location, it would be natural to think that the wave force or the speed of the tsunami were different by factors such as the depth of water or the submarine topography in this case. There was a house (Photo 7.4-17:10) remained in the area where there was no building and no protect forest existed in the direction of the wave. In addition, the relatively new Japanese conventional post and beam wood house (Photo 7.4-18 :11) and light frame construction house (Photo 7.4-19 :12) were confirmed at the location where there were no survived buildings in the direction of waves. Besides, in the downstream of the former, another Japanese conventional post and beam wood house (13) remained in. The water depth was estimated to be about 3.5 m in these locations.

In the downstream of large RC building, houses with low structural specification (Photo 7.4-20 :14) also remained, as shown in Photo 7.4-20. On the other hand, in the location where was the downstream of the relatively large factory building (Photo 7.4-21 :15), the wood house (16) with relatively better structural specifications avoided being carried away, selectively.

Photo 7.4-10. Wood house (1) that was carried away with the base in Yuriage, Natori city.

Photo 7.4-11. Steel tube pile left at the the original position (2) of house in photo 7.4-10.

Photo 7.4-12. Heavily damaged temple (3) building in Yuriage, Natori city.

Photo 7.4-13. Wood house with store (5) remained in the down-stream of the survived buildings in Yuriage.

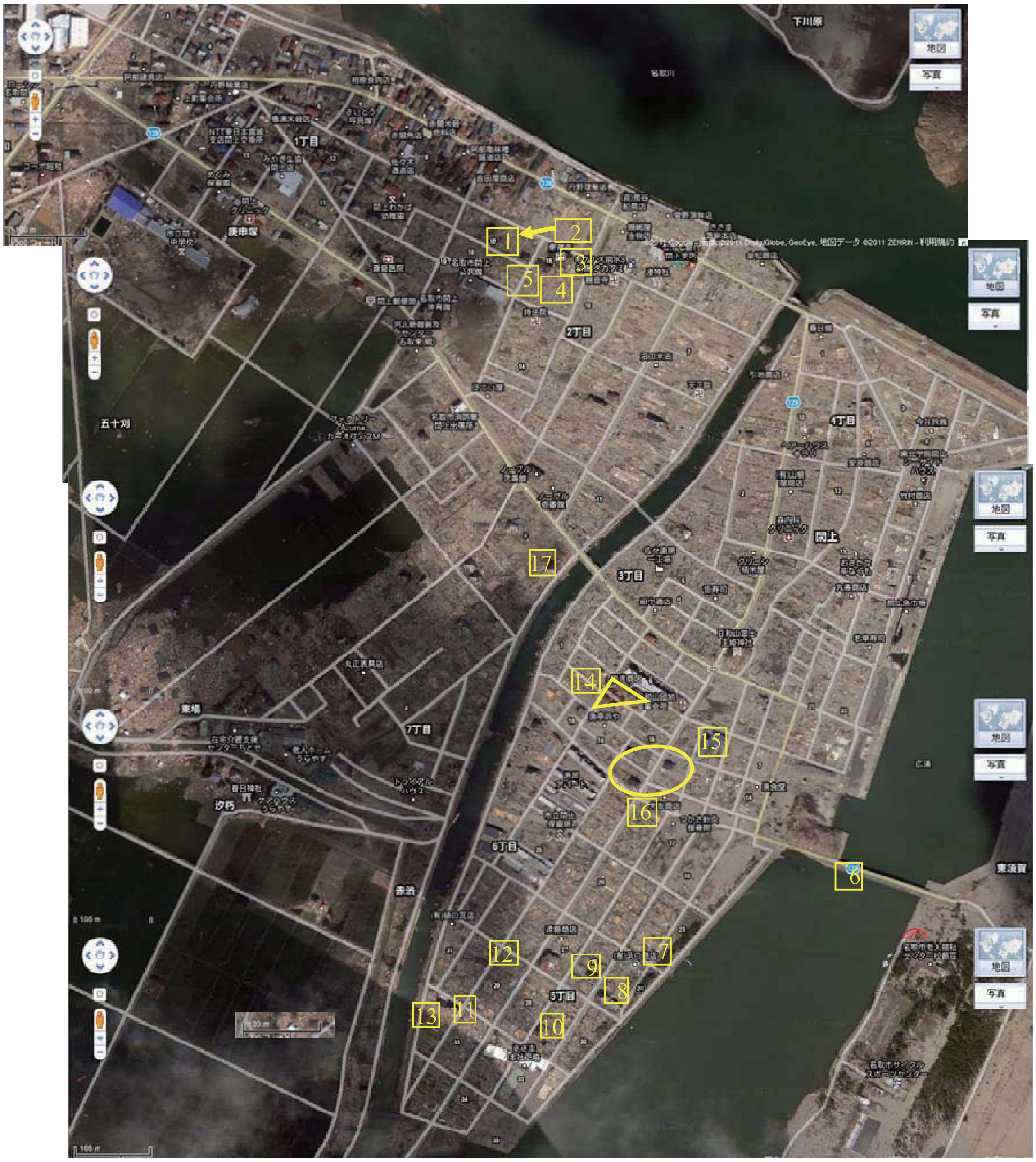

Fig. 7.4-2. Aerial photograph and the location related to surveyed buildings in Yuriage, Natori city.

Photo 7.4-14. Protect forest (7) in Yuriage, Natori city.

Photo 7.4-15. Fallen Protect forest and wood house (8) washed away in Yuriage, Natori city.

Photo 7.4-16. Protect forest and wood house (9) remained in Yuriage.

Photo 7.4-17. Wood house (10) remained without the effect of protect forest.

Photo 7.4-18. Japanese conventional post and beam wood house (11) remained alone.

Photo 7.4-19. Light frame construction wood house (12) remained alone

Photo 7.4-20. Group of wood houses (14) which were not washed away
in the downstream of a RC apartment house in Yuriage

Photo 7.4-21. Wood houses (15) which were not washed away
selectively in the downstream of a factory building.

(4) Remained wood buildings in Arahama, Watari town

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 Fig. 7.4-3. 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 water depth was estimated about 6 m. Many of wood houses were washed away. On the other hand, in the west area of the Arahama port, the water depth was estimated about 4 m. Many of wood houses remained. Remained parts, for example foundation, sill, and so on, were as mentioned in (1).

In the area between Pacific Ocean and Arahama port, remained wood buildings were Glulam frame structure (Photo 7.4-22) and a mixed structure (Photo 7.4-23) which has 1st story of RC structure and wooden 2nd story. In other cases, the part of the L-shaped wood house (Photo 7.4-24) whose part with short horizontal length in the direction of wave pressure was washed away, and another part with long horizontal length remained. It was confirmed that metal fasteners were used in the column end joints, and considered that the structural performance of this house was better.

In the north area of the Arahama port, a 3-story wood house (Photo 7.4-25) remained. The reason might be that the lateral strength of 1st story in 3-story building was larger than that in 2-story building.

In the west area of the Arahama port, it was confirmed that the wood house (Photo 7.4-26) was crashed by two ships but remained. The reason was that the wave pressure was low and the structural performance of the house was high because the house was relatively new.

Fig. 7.4-3. Aerial photograph and the water depth estimated in Arahama, Watari town.

Photo 7.4-22. Glulam frame structure remained in Arahama, Watari town.

Photo 7.4-23. Mixed structure which has 1st story of RC structure and wooden 2nd story.

Photo 7.4-24. L-shaped wood house whose part was washed away in the east of Arahama port.

Photo 7.4-25. 3-story wood house remained in the north of Arahama port.

Photo 7.4-26. Wood house remained in spite of ships' crashing in the west of Arahama port.

7.4.4 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. Fig. 7.4-4 shows the aerial photograph and the locations related to surveyed buildings. Similar to plain areas, many of wood houses were washed away by tsunami here in Oofunato. According to the resident of a house (Photo 7.4-27:1) located just near the shore, the height of the tsunami reached to the top of 2nd story, and the house went under the water completely. The house was damaged in a part, however it remained. The neighbouring work shed (2) whose sill came off from floor concrete moved. On the other hand, a 2-story wood house (Photo 7.4-28:3) opposite to the house (1) across the street along the sea suffered almost no damage. Two houses next to the house (1) and shed (2) remained. There is a hill in the back of them (in the north side), and there is a possibility that the hill affected the strength of the wave force caused by the tsunami. A Japanese traditional post and beam frame house (Photo 7.4-29:5) built on the street along the sea remained under the water depth of about 5-6 m, in spite of partial failure of walls. Close to this house, a wood house (Photo 7.4-30:6) remained under about 6 m water depth in spite of partial failure in the roof system. It was considered that this failure caused by the floating materials. There was a house (7) remained in the next, but a house which was guessed to have many hold down fasteners (8) was washed away. The house with hold down fastener may not remain by severe tsunami.

At the location where we went up the slope land from these houses, a light steel-frame house (9) remained in under the about 5 m water depth. In the next of this house, the 1-story old wood house (Photo 7.4-31:10) whose structural specification was not so good, but the anchor bolts were installed remained. In addition, a warehouse with mud walls (Photo 7.4-32:11) was remained and an old wood house without anchors (Photo 7.4-33:12) turned and moved horizontally. Because the wood house under about 5 m water depth were almost washed away in plain areas, it might be possible for the slope land to make lateral force caused by tsunami a little smaller.

Fig. 7.4-4. Aerial photograph and the locations related to surveyed buildings in Akasaki-cho, Oofunato city.

Photo 7.4-27. Wood house ([1]) remained under the water depth of over 7 m in Akasaki-cho, Oofunato city.

Photo 7.4-28. Wood house ([3]) without damage under the water depth of over 7 m in Akasaki-cho, Oofunato city.

Photo 7.4-29. Japanese traditional wood house ([5]) which was not carried away under about 5 m water depth in Akasaki-cho, Oofunato city.

Photo 7.4-30. Wood house ([6]) which was not carried away in spite of damage on 1st floor roof system in Akasaki-cho, Oofunato city.

Photo 7.4-31. Survived house ([9]) which seemed to have comparatively slight structural specifications in Akasaki-cho, Oofunato city.

Photo 7.4-32. Survived soil warehouse ([10]) which seemed to have comparatively slight structural specifications in Akasaki-cho, Oofunato city.

Photo 7.4-33. Survived old house (12) which rotated and moved horizontally in Akasaki-cho, Oofunato city.

7.4.5 Survey summaries

Results of surveys are summarized as follows;

1) Not all of the low-rise wood houses were washed away by the tsunami.
2) In the downstream of survived buildings more than a middle-rise or higher buildings, many wood houses remained regardless of structural specifications.
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) In the location where there were almost no survived buildings in the direction of tsunami, there were some cases that a wood house remained alone. In that case, there were many examples that some columns or walls were carried away in the direction where tsunami came.
5) Having metal fastener or not in the column end joints such as the hold down fastener didn't decide whether the house was carried away or remain in.
6) It was possible for the slope land to make lateral force caused by tsunami a little smaller than in plain areas.

7.5 Conclusion

This paper classified the damage patterns for different structural categories and briefly discussed the factors that had caused various types of damage. Based on the results of the relevant investigation, the survey team is now conducting an additional site investigation as required and collecting design documents for damaged buildings, while further evaluating the effects of building openings and buoyancy and proceeding with the elucidation of mechanisms for causing damage and the identification of tsunami loads on buildings.

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