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BEHAVIOR OF RC STRUCTURES UNDER TSUNAMI TRIGGERED BY THE GREAT EAST JAPAN EARTHQUAKE

Carlos CUADRA[1]

SUMMARY

The present report describes the characteristics of damages and behavior of reinforced concrete buildings during tsunami action. The discussion is based on the field damage survey in selected cities located on the coast of the zone affected by the Great East Japan Earthquake on March 11, 2011. This earthquake is the most powerful know earthquake that has hit Japan with a magnitude 9.0 and with epicenter located at 129 km of Sendai city (off the coast). The earthquake triggered a destructive tsunami with run up height of up to 40 meters that mainly affect cities located on the Pacific Ocean coast of the Tohoku region (north-east region of Japan). Reinforced concrete buildings in general resist the tsunami without collapse however the non-structural elements like panels and ceilings were severely damaged. The analysis of damages has permitted to understand the behavior of RC buildings under tsunami attack, and has also permitted to establish recommendations for their use to take refuge from tsunami in places where natural topography makes impossible to reach hilltops or other safer places.

INTRODUCTION

An earthquake with a magnitude of Mw 9.0 struck the north-east part of Japan (Tohoku region), on 11 March 2011 at 14:46 local time. This earthquake is the most powerful know earthquake that has hit Japan with its epicenter located at 129 km of Sendai city. The earthquake triggered a destructive tsunami with run up height of up to 40 meters. The tsunami affects mainly cities located on the Pacific Ocean coast of Iwate, Miyagi and Fukushima prefectures the Tohoku region, and also Ibaraki prefecture in Kanto region. Wooden structures were destroyed by the tsunami action when the water depth reaches or covers at least the first floor of the building. These wooden structures were the most vulnerable constructions that were washed up by the tsunami. Steel frame structures and steel trusses that are used mainly for industrial constructions suffered heavy damages of walls, ceilings, finishing panels and non-structural elements. In some cases the failure of these non-structural components produced the failure of structural elements and even the collapse of the structure.
In the case of reinforced concrete buildings in general resists the tsunami without collapse, however the non-structural elements like panels and ceilings were severely damaged. However, in some cases low rise RC buildings were tilted by the tsunami action. In this report, the characteristics of the damages and behavior of RC buildings during the tsunami action is discussed based on the field survey of the damages in selected cities located on the coast of the affected zone.

[1] Associate Professor, Akita Prefectural University, Japan. Email: carlos@akita-pu.ac.jp

The analysis of the damages characteristics has permitted to understand the behavior of this kind of building and has also permitted to establish recommendations for their use to take refuge from tsunami in places where natural topography makes impossible to reach hilltops or other safer places.

SELECTED AREA AND DAMAGES

The damages on building structures that were produced by the tsunami are described in this section and in special the damages that occurred on reinforced concrete structures. However it is necessary to mention that damages are not limited only to building structures. Tsunami affected also many infrastructures like ports, embankments, roads, railroads, oil tanks, and in its more dramatic damage affected the nuclear power plant of Fukushima. Environmental damages were also reported like the chlorination of agricultural soils, sedimentation of debris near ports, transportation of old industrial and mine residues from the sea bottom to the ground surface, etc.
The sites that were selected for the present survey are shown in Fig. 1. Cities of Ofunato, Rikuzentakata, Kesennuma, Ishinomaki and Onagawa were visited to perform the corresponding survey. The Fig. 1 shows that the shape of the coast line is intricate with coast lines that converge forming shapes like river deltas that facilitate the run-up of the tsunami. In the case of Ishinomaki city that is located in the lower left corner of the figure the coast line is straight however the large portion of the city is located parallel to this coast line and therefore the inundation area was large in comparison with other cities. On the other hand high ground level in Ishinomaki city is located a little far away of the coast line.

Figure 1 : Zone of survey (Google map)

Table 1 shows the extension of the inundated area and the number of family units in selected cities of this survey. The number of affected families and the extension of the inundated area are larger for Ishinomaki city. The extension of inundation area was large due to the location of ports on lower ground along the coast line. On the other hand, Onagawa city is the zone with the smallest inundated area however the number of victims (deaths and disappeared) was of the order of 1000 persons (1/4 of the number of affected families) and in the case of Ishinomaki victims reached 4000 persons (1/10 of the number of affected families). The high rate of victims of Onagawa city was due to the topographical condition of the location of the city with a very narrow area between the coast line and the surrounding hill. This condition originated that the tsunami reached high inundation depths and it is also supposed that the successive waves of the tsunami produced a violent flows of the sea water.

Table 1: Inundated area and affected families in the investigated cities

Prefecture	City	Inundated Area	Number of affected families
Iwate	Ofunato	8 km^2	6,957
	Rikuzentakata	13 km^2	5,592
Miyagi	Kesennuma	18 km^2	13,974
	Onagawa	3 km^2	3,155
	Ishinomaki	73 km^2	42,157

DAMAGES ON BUILDINGS

To compare the damages of reinforced concrete, also damages on wooden structures and steel structures are described as references. In general the wooden structures collapsed when were attacked by the tsunami. The steel structures remain stand up however the finishing walls, ceilings and other non-structural elements fails and in some cases these failures originate the failure of the main structure. The reinforced concrete structures presented better behaviour and were the structures that in general remain in their original location without structural damages. This can be explained by the high lateral stiffness of the reinforced concrete buildings in comparison to steel structures and wooden structures. The wooden structures have the smaller lateral stiffness and in general were washed up when the tsunami reached or covered the first floor. The relation between the damages and the earthquake resistant characteristics of these three types of structures are summarized in Table 2.

Table 2: Relation of Earthquake resistant forces and damages due to Tsunami

Type of structure	Earthquake resistant force for design	Level of Tsunami damages
Wooden structure	Low	High
Steel structure	Medium	Medium
Reinforced concrete	High	Low

Damages on wooden houses

From damage surveys reported by other authors, it is recognized that in general the wooden houses collapse or present damages due to the tsunami action when the inundation depth is larger than 2 meters. As is presented in Figure 2, the damages on wooden houses are divided into three zones according to the inundation depth. Zone A correspond to a places where the inundation depth is smaller than 2 meters and structural damages are not observed, that is the wooden houses are safe in this case. Zone B correspond to a zone where the inundation depth ranges from 2 to 4 meters, and depending on the structural shape and condition of the structural elements, the houses can suffer from light damages to severe damages. From the field observation it can be said that when the water level cover the first floor of the wooden house the structures collapse not only due to the lateral force of the water but also due to the water pressure on the ceiling of the first floor causing floating of the upper floors. Zone C correspond to a zone where the inundation depth is large that 4 meters and total collapse of the structure is expected to occur.

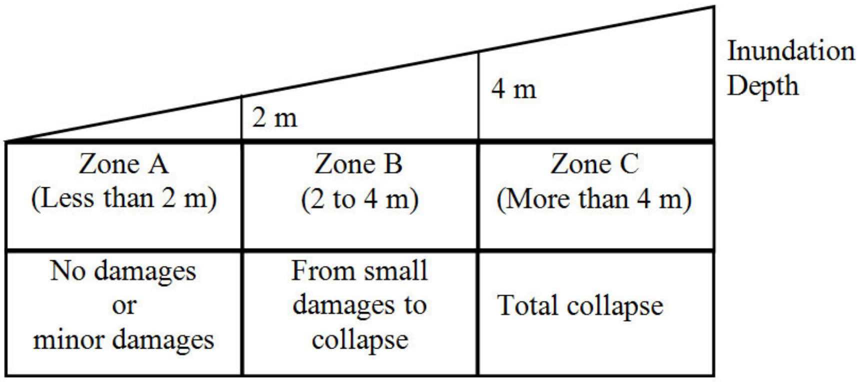

Figure 2: Inundation depth and damages on wooden houses

Figure 3 shows some typical damages on wooden houses that were produced by the tsunami. In Figure 3(a) it can be observed that wooden houses were completely destroyed by the tsunami action. It can be also observed that houses located on high sites are not affected. In Figures 3(b) and 3(c) the first floor was destroyed by the tsunami and the upper parts of the houses were transported and then left by the tsunami on a different place from their original location. In the case of Figure 3(d) the tsunami destroyed the first floor and also produced the overturning of the remaining upper floor.

Figure 3: Damages on wooden houses

Damages on steel structures

Steel structures are used in general for industrial facilities and office buildings. Most of the buildings are framed structures and structural elements like beams and columns are slender elements. Floors and walls are made of light panels and the lateral stiffness is appropriately designed to resist the earthquake force. However during the tsunami attack the water pressure acting on panels or in general in elements of large area generated large lateral forces that destroyed that non-structural elements and in some cases the failure of these elements lead to the failure and even to the collapse of the main structure.

Damages on Steel structures can be observed in Figure 4. When the inundation depth reaches only the first floor the structure remains almost intact however the wall panels of the first floor suffered some damages as can be observed in Figure 4(a). In Figures 4(b) and 4(c) the inundation depth reached the second floor and wall panels and ceiling are destroyed. In this case the structures remain stand up however some local failure of the structural elements were observed. Figure 4(d) shows a total collapse of steel structures. In this case the building was completely covered by the water.

Figure 4: Damages on steel structures

Damages on RC structures

Many reinforced concrete structures resisted the tsunami action without collapse as can be observed in Figure 5. Figure 5(a) is the building of a local bank located at Ofunato city, and it can be observed from the damages of the windows and the damage of the advertisement panel of the left corner of the building that the tsunami reach the third floor. In Figure 5(b) it is also inferred that the tsunami covered the 2-story building by observing that the windows glasses were destroyed and now are replaced by wood panels. Figure 5(c) is an apartment building located at Rikusentakata city and from the damages of the balconies it is inferred that the tsunami reaches the fourth floor. Detailed of the damages of the balconies can be observed in Figure 5(d), where the panels of the balconies of the fifth floor are intact while the panels of the lower floors are completed destroyed.

Figure 5: RC buildings after tsunami attack

Figure 6 shows the condition of a hotel building located very near the shoreline in Rikuzentakata city. The building resists the tsunami attack however the lower floors suffered the destruction of the non-structural elements and also, as it is observed in the Figure 6(a), the damage of a reinforced concrete wall due to the lateral water pressure. In this building it was also observed that the cover concrete of structural elements like columns was spall-out, probably due to a combination of earthquake vibration action and posterior tsunami action as can be observed in Figure 6(b).

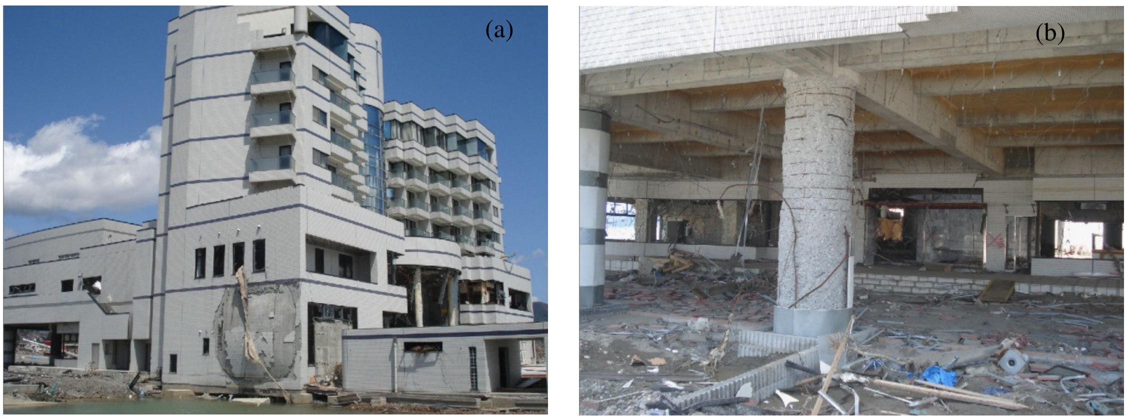

Figure 6: Condition of RC Building (hotel) near shoreline

In general reinforced concrete buildings did not collapse however under certain conditions the tsunami action caused the overturning and even the translation of building from its original location. This was reported by a survey team of the Tohoku Branch of the Architectural Institute of Japan (ref. 5) and verification survey was carried out by the author. These damages occurred at Onagawa town and the affected buildings were buildings with weak foundation, and with shape like boxes that do not permit the transit of the water and facilitate the action of the floating force. In Figure 7 damages of these buildings are shown.

Figure 7: Damages on Reinforced Concrete buildings

Figures 7(a) shows an overturned 3-story building with a shape of box and few openings. This building was completely covered by the tsunami water and as it is shown in Figure 7(b) it has a sallow slab foundation that together with the shape of the building facilitates the action of the floating forces. Figure 7(c) shows the overturning of a 2-story building with exposition of the pile foundation. The use of piles for lower rise buildings indicates the poor quality of the foundation ground. On the other hand in the Figure 7(d) it can be observed that the building has suffered the impact of some body (probably a ship) that could originate the overturning of the building.

CONCLUSIONS

Behaviour of reinforced concrete building during the tsunami action originated by the Great East Japan Earthquake on March 11, 2011 was discussed by comparing their damages with those of other type of constructions. Reinforced concrete buildings in general resist the tsunami without collapse however when constructions present shallow or weak foundation and building shapes induce the action of the floating force, overturning of the building was observed. In the case of not collapsed buildings severe damages on non-structural elements like panels and ceilings were observed.
If reinforced concrete buildings are intended to be used as refuge, buildings of more than four floors or more than 15 meters are recommend. It is also important to check the condition of the foundation of the

structures that are designated as refuge since the failure of the foundation could originate the overturning of the building. Additionally, this selected building must be verified to resist some impact forces or in any case must be located in places where the impact of displaced ships or other building can be avoided.
The survey has permitted to understand the behaviour of reinforced concrete buildings under tsunami attack and it can be state that these kind of buildings could be used to take refuge from tsunami in places where natural topography make impossible to reach hilltops or other safer places.

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