E3S Web of Conferences **331**, 07011 (2021) https://doi.org/10.1051/e3sconf/202133107011
ICDMM 2021

Hard and soft measures for earthquake and tsunami disaster mitigation

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Abstract. A destructive earthquake struck the Kobe region on January 17, 1995, and a massive earthquake and tsunami struck eastern Japan on March 11, 2011. We present an overview of the casualty aspects of the 2011 Tohoku earthquake compared with those of the 1995 Kobe earthquake. In the Tohoku disaster, some water gates and seawalls saved some villages from the tsunami effects, though some did not. Based on these examples, we discuss the efficiency of soft and hard measures and consider their respective merits and demerits. The main causes of death in the Kobe and Tohoku EQs were, respectively, collapsing buildings and drowning in the tsunami. Although the time to death was very short in both cases, people often have more time to evacuate in the case of an interplate earthquake leading to a tsunami. Basic countermeasures against tsunamis include such hard measures as water gates, seawalls, and embankments. Soft measures need to be implemented in areas where hard measures are insufficient

1 Introduction

A massive interplate earthquake struck eastern Japan on March 11, 2011. A moment magnitude, M_W, of 9.0 and maximum seismic intensity of 7 were recorded in the city of Kurihara, Miyagi Prefecture. As of May 10, 2013,the total numbers of dead, missing, and injured people were 15,883, 2,676, and 6,144, respectively. Most of the casualties were caused by the subsequent tsunami. The numbers of buildings that completely collapsed, partially collapsed, and burned down were, respectively, 126,419, 272,017, and 297 [1]. In addition, extensive parts of the infrastructure, such as road, rail, gas, water, and sewage systems, sustained considerable damage. The following is an outline of the damage.

The geotechnical effects outside the tsunami-struck area included widespread ground liquefaction in port and reclaimed land areas, earth dams, and embankments as well as slope failures. Damage caused by shaking buildings was observed throughout the Tohoku region, but there was a remarkable lack of major damage beyond the run-up area. Slope failures and disrupted sidewalks occurred along roads. Some bridges sustained damage, though most bridges were undamaged. Some coastal bridges were washed away by the tsunami. Areas of coastal local railway were destroyed at several locations by the tsunami and were out of service for several months or more. The main Shinkansen line sustained damage to its viaduct columns near the city ofSendai, though there was no significant structural damage except to some electric poles along viaducts. Inaddition to nuclear power plants, several fossil fuelpower plants went out of service because of their coastallocations. Owing to telecommunications failure, traffic congestion occurred just after the earthquake, though cell towers and services were soon restored. Gas, water, and wastewater systems were generally soon restored with few excavations being required for pipe replacement beyond the run-up area. Washout of oil tanks led to fires in several coastal areas, though several large oil tanks were observed that showed nosigns of spillage or other damage. Ports sustained heavy damage as a result of the tsunami, particularly quayside areas through ground liquefaction.

In this paper, we first present an overview of the casualty aspects of the 2011 Tohoku earthquakecompared with those of the 1995 Kobe earthquake. In the Tohoku disaster, some water gates and seawalls saved some villages from the tsunami effects, though some did not. Based on these examples, we discuss the efficiency of soft and hard measures and consider their respective merits and demerits.

2 Human Casualties of Kobe and Tohoku Earthquakes

A destructive earthquake struck the Kobe region on January 17, 1995. Most kinds of earthquake damage to buildings, houses, lifelines, railways, roadways, and harbours occurred. Figs. 1 and 2 indicate the damage to a highway viaduct, which became one of the symbolic scenes of the Kobe earthquake. Fig. 3 shows that the rate of collapsed and severely damaged houses wassignificantly different according to whether the buildings were

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constructed before or after 1981[2] the year when the seismic code for building construction was revised. This figure indicates that severe damage leading to casualties could have been reduced if houses constructed before 1981 had been strengthenedaccording to the provisions of the revised code.

Fig. 1. A bus hangs over the edge of the collapsed highway

Fig. 2. Collapsed pillar of a highway viaduct caused byshear failure

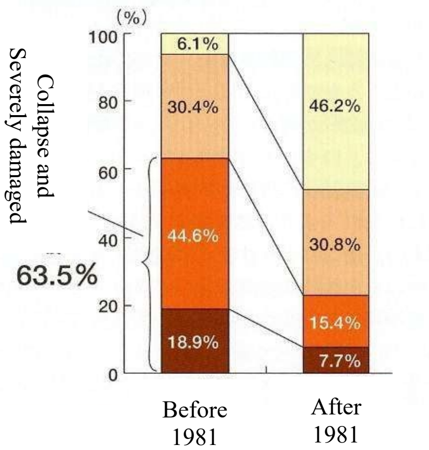


Fig. 3. Histogram representation of the proportion of structural damage according to the construction year— before and after 19812)

2.1 Causes of Death

Fig.2 shows a classification of the causes of death [2]in the 1995 Kobe earthquake (Kobe EQ). Over 80% of deaths were caused by collapsing buildings. This fact became the basis for promoting the strengthening of buildings. However, the causes of death in the 2011 Tohoku earthquake (Tohoku EQ) were quite different from the Kobe EQ, as shown in Fig. 5 [3]: more than90% of the deaths were due to drowning.

The time leading to death after being trapped in a collapsed building is classified according to the injured part of the body, as indicated in Fig. 6 [4]. In this figure, the horizontal axis represents time (hours) on a log scale, and the vertical axis is an index value between 0 (death)and 1 (survival). For example, a person survives only fora period of several minutes if they are trapped andsuffocated or are crushed by the debris (mode 1), but cansurvive for several days if they become trapped withoutsustaining any injury. In the Kobe EQ, as noted, most ofthe victims were killed by collapsed houses (Fig. 5), which falls in the category of mode 1, and those deaths occurred in buildings that predated the code revisions (Fig. 3). That is why the government promoted theintroduction of hard measures, such as the strengthening ofhouses.

In comparing the main causes of death in the two earthquakes, the difference like the disasters complicates the casualty issue. Casualties in the Kobe EQ were due to the tremor itself, whereas in the TohokuEQ the casualties were largely due to the tsunami. Both sets of casualties fall in the same category of mode 1, mentioned above. In a tsunami disaster, people often have time to prepare for evacuation, especially in the case of an interplate-type earthquake. Hard measures are effective for preventing damage caused by tremors; however, soft and hard measures should be adopted for a tsunami disaster by efficiently using the available time.

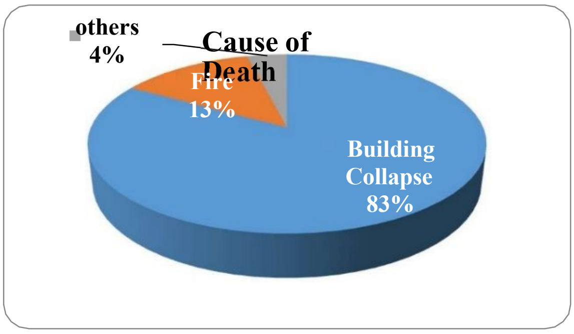


Fig. 4. Pie chart illustrating the causes of death in the 1995 Kobe earthquake [2]

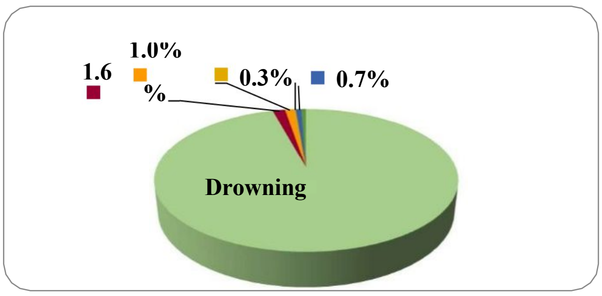


Fig. 5 Pie chart illustrating the causes of death in the 2011 Tohoku earthquake [3]

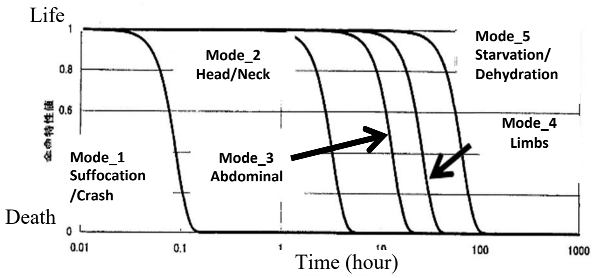


Fig. 6. Graph indicating the time leading to death after being trapped in a collapsed house [4]

・Cause damage: tall, heavy furniture
・Prevent damage: short furniture, table

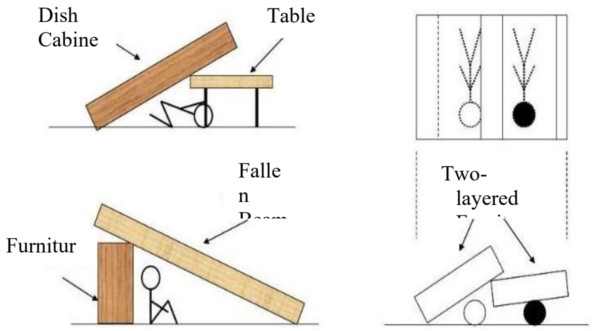


Fig. 7. Schematic representation of interior damage occurring in a house during an earthquake

In addition to the buildings themselves, household furniture is often a cause of human casualties in earthquakes. There is much anecdotal evidence to suggest that tables prevent injury from falling cabinets and other items of furniture. In general, tall, heavyfurniture items become dangerous objects, whereas tables and low furniture items provide shelter fromfalling beams, walls, and larger furniture items. In the Kobe/Tohoku EQ, it was reported that a falling piece ofdouble-layered furniture killed one person but protectedanother Fig. 7.

2.2 Rate of dead, missing, and injured persons

From the death and injury rates for the 2011 Tohoku, 1995 Kobe, 1896 Meiji Sanriku, and 1933 Showa Sanriku earthquakes [5], there are more injuries than deaths with an intraplate earthquake, such as the Kobe EQ; however, interplate earthquakes with tsunamis, such as the Tohoku, Meiji Sanriku, and Showa Sanriku earthquakes, resulting in more dead than injured people.

A famous news video taken in Banda Aceh during the 2004 Sumatra earthquake showed a tsunamiadvancing along a street. Initially, it proceeded at a walking pace; however, within tens of seconds, the wavevery quickly increased its speed. A similar situation occurred in many cities and towns along the coast in the2011 Tohoku EQ. It is possible to learn many lessons from past disasters.

3 Early warnings and Tsunami damage

3.1 Tsunami alerts and early warnings

The location and magnitude of an earthquake are determined within about 3 minutes in Japan and are immediately reported on TV and radio [6]. If the earthquake is not tsunamigenic, the message “Tsunami is not expected” is added to the report. However, if a tsunami is expected, the Japan Meteorological Agency (JMA) issues a forecast about the height of the tsunami and the arrival time of the initial wave, as shown in Fig.
8. The JMA calculates several tens of thousands of cases for potential tsunamis around the islands of Japan and in the Pacific Ocean, and the appropriate information is presented as forecasts and warnings. If the estimated height of a tsunami is greater than 3 m, a large tsunami warning is announced; if the estimated tsunami height is less than 0.5 m, the JMA announces a tsunami advisory warning.

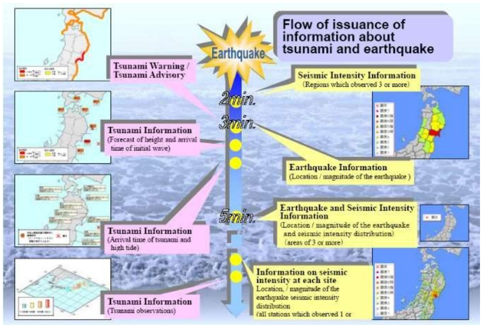


Fig. 8. Information flow-diagram relating to tsunamis and earthquakes issued by the Japan Meteorological Agency [6]

3.2 Tsunami alerts announced by the JMA in the 2011 Tohoku EQ

Table 1 presents the details of information about tsunamis released by the JMA for the Tohoku EQ. From this data, it is evident that the JMA made a tsunami announcement 4 minutes after the earthquake occurred (at 14:50). This first alert for the tsunami height by the JMA indicated 3 m, 6 m, and 3 m for Iwate, Miyagi, and Fukushima prefectures, respectively, with a magnitude of 7.9. This estimate meant that a 3-m-high tsunami had already struck the seashore of Iwate Prefecture and that 6- and 3-m-high tsunamis would strike Miyagi and Fukushima prefectures, respectively, 10 and 20 minutes later. All the tsunami heights were underestimated, but the magnitude of the earthquake was also underestimated. Twenty-eight minutes after the earthquake occurred (at 15:14), the arrival of the tsunami was confirmed in these three prefectures, and the tsunami heights were 6 m, over 10 m, and 6 m for Iwate, Miyagi, and Fukushima prefectures, respectively. The magnitude was still recorded as 7.9. After 45 minutes (at 15:31), tsunamis ofover 10 m in height, were eventually confirmed in each
Prefecture. Concerning the magnitude of the earthquake, it took an additional two days before the final value of 9.0 was released. We do not intend to criticize the difference between the estimated and actualvalues, but it should be noted that estimating a tsunami’sheight and arrival time is difficult even when high technology is employed.

Table 1. Time sequence of tsunami alerts and magnitude announcements from the JMA

Time (Mar 2011)	M	Iwate		Miyagi		Fukushima	
		arrival	height	arrival	height	arrival	height
11/14:46	Earthquake occurred						
11/14:50	7.9	Est.	3m	15:00	6m	15:10	3m
11/15:14	7.9	Conf.	6m	Conf.	>10m	Conf.	6m
11/15:31	7.9	Conf.	>10m	Conf.	>10m	Conf.	>10m
11/16:00	8.4	Magnitude modified					
11/16:09	8.4	Conf.	>10m	Conf.	>10m	Conf.	>10m
11/17:30	8.8	Magnitude modified					
11/18:47	8.8	Conf.	>10m	Conf.	>10m	Conf.	>10m
13/12:55	9.0	Magnitude modified					

3.3 Tsunami damage

Several scenes showing the damage caused by the tsunami appear in Fig 9–14. The extreme power of thetsunami is evident in the damage to buildings, harbours, lifelines, railways, roadways, industry, and agriculture.

The following sections deal with two villages in Iwate Prefecture—Fudai and Taro, as shown in Fig. 7. Each village had developed its hardware countermeasures to prevent damage from tsunamis.

Fig. 9. Damaged pipe behind a seawall

Fig. 10. Damage caused by fire after(Kita-ibaragi)

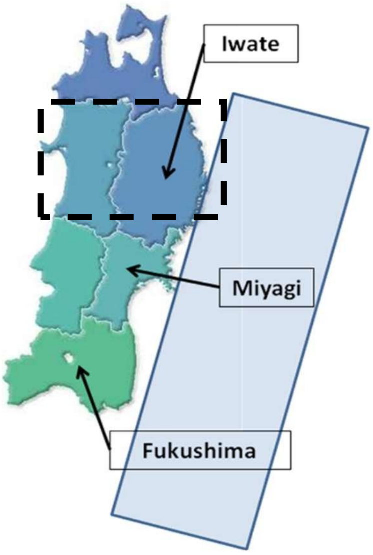
Fig. 11 Ricefield covered with seawater (Soma)

Fig. 12. Fallen pine trees (Soma)

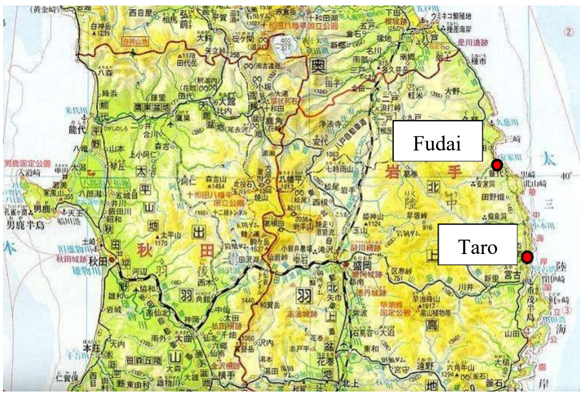
Fig. 13. Buckled crane arm (Soma)

 https://doi.org/10.1051/e3sconf/202133107011

Fig. 14. Damaged railway station (Shinchi)



(a) Three prefectures in the Tohoku region



(b) Fudai and Taro

Fig. 15. Map of the Tohoku region and the location of Fudai and Taro

3.3.1 Watergate in Fudai

The Fudai watergate was constructed in 1984 at a distance of about 300 m from the coast (Figs 16 and 17).The height of the gate is TP+15.5 m and the total crest length of the four gates is 205 m. The village itself is located several hundred meters inland from the coast. Fudai experienced tsunamis associated with the 1896 Meiji Sanriku and 1933 Showa Sanriku earthquakes, which had magnitudes of 8.25 and 8.1, respectively5). In 1896, the tsunami struck the village and casualties were severe: 1,010 people were killed. In the Tohoku EQ, the tsunami height was estimated as 20 m, and so the tsunami exceeded the water gates and run-up. Fortunately, no fatalities were reported in the village after the Tohoku EQ.

3.3.2 Seawalls in Taro

The village of Taro has had an unfortunate history concerning tsunami damage. In the 1896 and 1933 earthquakes, 1,859 and 911 people were killed and tsunami heights of 15 m and 10 m, respectively, were recorded. After the 1933 Showa Sanriku tsunami, the village began constructing seawalls in three stages:1934-57; 1962-65; and 1973-78. They are depicted in Fig.11 and Fig. 8

Fig. 16 Fudai water gate (downstream side)

Fig. 17. Satellite image of the Fudai area

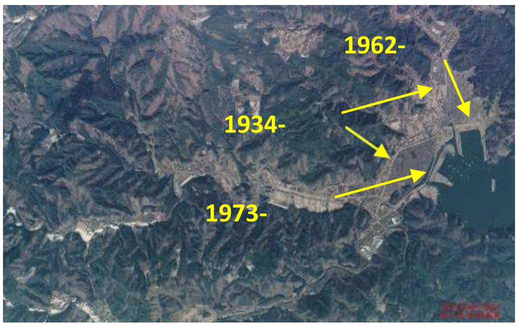


Fig. 18. Location of seawalls in taro

Fig. 19. Location of evacuation shelters in Taro

(a) During Tsunami

(b) After Tsunami (Fig (b) courtesy of Mr. Hatayama, from Sankei New:http://sankei.jp..msn.com)

Fig. 20. Tsunami sweeping over the 10 m high seawall at Taro

Fig. 21. The tsunami washed houses away in Taro

With the Tohoku EQ, a tsunami of over 10 m in height struck Taro, and many residents expected the seawalls to protect them. The tsunami swept over or destroyed the seawalls Fig. 20.

Fig. 21 shows the town after the tsunami. In all, 1,609 houses were destroyed in this area. The totalnumbers of dead and missing people8) for the whole ofMiyako, which comprises six districts including Taro, were 417 and 195, respectively, as of June 17, 2011 [4].

4. Tsunami Countermeasures

The basic hard countermeasures against tsunamis are such structures as water gates, seawalls, and embankments. Even though the tsunami flowed over the watergate in Fudai, the village was protected.

The term "hard" here is defined as structures constructed for the specific purpose of disaster mitigation. Conversely, "soft" indicates information, information-transmission measures, and information systems. An information-acquisition system usually requires hardware, but the main purpose of the system is the transmission of information.

One example of a successful system combining soft and hard measures is an alert system used by Japan's railways called the Urgent Earthquake Detection and Alert System (UrEDAS) [9]. This system includes data-acquisition, decision-making, and electricity shutdown processes. Japan Railways East reported that at the timeof the Tohoku EQ, five Shinkansen trains were running between Fukushima and Iwate prefectures at speeds of around 270 km/h; however, all the trains successfully decelerated and stopped quickly before the main tremor through the UrEDAS system [10]. In the 2003 Sanriku-minami earthquake, many columns of the Tohoku Shinkansen viaduct were severely damaged and retrofitted using steel plate Fig. 22. The bridge columns of the Tohoku Shinkansen sustained severe damage in the Tohoku EQ Fig. 23; however, the retrofitted columns suffered no damage at all.

Recently, the Central Disaster Prevention Council of Cabinet Office, Government of Japan [11], publisheda midterm report regarding proposals for tsunami countermeasures.

Fig. 22. Strengthened viaduct columns after 2003 Sanriku-minami-earthquake

Fig. 23. Damaged viaduct columns of the Tohoku Shinkansen line after the Tohoku earthquake (photo courtesy of Dr. Takahashi, DPRI, Kyoto Univ.)

In the report, some basic ideas for tsunami estimation were proposed. The report proposed that two levels of tsunami should be considered: (1) thefirst level includes tsunamis that cause extensive damage, although their frequency is very low; (2) the second level includes tsunamis that cause great damage, although their frequency is higher and the tsunami height is lower than with the first level. The first level demands the construction of comprehensive countermeasures, and these cover land-use policies, erecting evacuation buildings, and setting up disaster-prevention facilities combined with key soft measures, such as residents' evacuation.

In Japan, people usually start evacuating during a disaster based on the information given by the JMA. If the tsunami height in the Tohoku EQ had been 3 m, the seawalls of Taro would have successfully protected the village from the tsunami. The accuracy of information is extremely important, but the most difficult issue concerns the combination of soft and hard measures. There is a tendency for people to implicitly rely on hard measures once they have been put in place.The residents in Taro put their trust in the 10-m-high seawalls, which were designed to afford protection against the 10-m-high tsunami of the 1933 Showa Sanriku earthquake, even though the village experienced a 15-m-high tsunami in the 1896 Meiji Sanriku earthquake.

Syuto (1992) [12] proposed a relationship between tsunami intensity and damage. In his paper, he pointed out that the lack of accurate data had a great effect on damage to buildings. Supporting hard measures with soft measures demands more accurate information relating to the tsunami height and arrival time than is currently available. In particular, research has to beconducted into the effects of tsunami pressure on different structures.

5 Conclusions

An outline of the destructive Tohoku EQ of March 11, 2011, was presented. From the discussion, the following results emerged.

1) The main causes of death in the Kobe and Tohoku EQs were, respectively, collapsing buildings and drowning in the tsunami. Although the time to death was very short in both cases, people often have more time to evacuate in the case of an interplate earthquake leading to a tsunami.
2) Basic countermeasures against tsunamis include such hard measures as water gates, seawalls, and embankments. Soft measures need to be implemented inareas where hard measures are insufficient.
3) Necessary elements among the soft measures that serve to support hard measures are swift operation, data accuracy and reliability, implementation of disaster plans, and achieving cooperation among residents.
4) For supporting hard measures with soft measures, information relating to tsunami height and arrival time is currently insufficient. In particular, research has to be conducted into the effects of tsunami pressure acting ondifferent structures.

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