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Factors Influencing Successful Mitigation of Tsunami Hazard: Lesson learned from the 2011 Tohoku Earthquake and Tsunami

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Abstract

Japan is one of the countries most affected by earthquakes. On March 11, 2011, Japan experienced a significant seismic event on the east coast of Tohoku, resulting in a 10-meter tsunami wave that caused damage to coastal cities in Tohoku and Iwate provinces. We are pleased to report that Fudai City was able to cope with the tsunami disaster in a way that avoided severe damage compared to other cities. This study aims to gain insight into the factors that contributed to the successful mitigation implementation in Fudai City and to identify the factors that led to the failure of mitigation in other cities. In this research, we have opted to employ a method that entails a comprehensive review of existing research studies. The findings of this study suggest that the success or failure of tsunami disaster mitigation in Tohoku may be influenced by a number of factors, beyond the mere implementation of structural mitigation measures such as the construction of seawalls and breakwaters. These factors may include land use regulations and zoning of coastal cities, the level of awareness and ability of the public to evacuate, and the availability of evacuation shelters and evacuation warnings..

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INTRODUCTION

Japan is an archipelago located on the coast of the Pacific Ocean, east of the Asian continent—and it's the only country in the world that can make that claim. Japan is divided into 47 prefectures, which are further divided into cities and villages. Geographical data shows that 70% of Japan's territory is mountainous. These areas are undoubtedly steep and dangerous to live in due to the significant risk of landslides. The Japanese people form settlements on coastal areas. Japan is located on the Pacific Ring of Fire, where three tectonic plates converge, making it prone to frequent earthquakes and volcanic eruptions. In addition to these natural disasters, ongoing earthquakes can cause other hazards like recurrent tsunamis in offshore areas. Japan is a global leader in tsunami disaster prevention, with robust precautionary measures and evacuation plans in place.

The Sanriku Coast, located in eastern Japan between the prefectures of Iwate, Miyagi, and Fukushima, has a history of being severely affected by tsunamis. The area has experienced repeated tsunamis. These include the Jogan tsunami in 869, the Keicho-Sanriku tsunami in 1611, the Meiki-Sanriku tsunami in 1896, the Showa-Sanriku tsunami in 1933, the far-field tsunami from Chile in 1960, and the Great East Japan tsunami or Tohoku tsunami in 2011 (Nobuo, 2009; Uppasri et al., 2013). These tsunamis occur on average every 37 years, and the main cause is 8-9 magnitude earthquakes (Uppasri et al., 2013). The Tohoku tsunami was one of the largest tsunamis in history, caused by an earthquake with a magnitude of 9.0. It reached a maximum height of 40 meters in Miyako City and Omoe Ayenoshi. Tsunami events in Japan will occur again within the expected interval.

The Japanese government took action based on these recurring events. They began investing public revenue in structural mitigation, building breakwaters along the Sanriku coastline. The goal is to protect coastal towns from the threat of a predicted tsunami. The breakwater is located in the towns of Kamaishi and Ofunato. The breakwater is the deepest of its kind, measuring 63 meters in depth and spanning 900 meters in length. The breakwater was designed to withstand the power of tsunamis similar to the Meiji tsunami in 1896 and the 1960 Chile tsunami.

However, the Tohoku tsunami in 2011 proved to be more powerful and taller than had been predicted. The tsunami caused major damage to the breakwater and submerged the city. Furthermore, the seawall that had been planned on the coast as protection after the breakwater could not withstand the tsunami. The tsunami exceeded the height of the planned seawalls in Iwate, Miyagi, and Fukushima prefectures, destroying them (Prabath et al., 2016) Furthermore, tsunami backflow can and does cause the destruction of seawalls and coastal dykes (Hazarika & Kasama, 2013; Nateghi et al., 2016)

While most cities in Iwate, Miyagi, and Fukushima prefectures were affected by the tsunami, Fudai City in Iwate Prefecture was a clear success story in the application of seawall structure mitigation. Fudai City successfully avoided severe damage from the Tohoku tsunami (Ogasawara et al., 2012).

Previous research clearly shows that while the government failed to implement structural mitigation to prevent the impact of tsunamis, not all cities were affected by the 2011 Tohoku tsunami. Fudai City is an excellent case study in how to successfully handle disasters, in contrast to other cities such as Taro City and Kamashi City. It is crucial to identify the successes and failures in great detail.

This research will identify the critical factors that must be incorporated into tsunami disaster mitigation planning. The failures and successes of cities that faced the Tohoku tsunami reveal which factors should be improved and which should be avoided in the planning and implementation of tsunami disaster mitigation that is likely to occur again. The results of this literature review are a vital reference for planning tsunami-resilient cities in countries prone to such disasters, such as Indonesia.

METHOD

This research employs a robust literature review using secondary data sources obtained from several articles. We will study the following variables: land characteristics, disaster characteristics, previous tsunami countermeasures, tsunami-resistant structural materials, and community mitigation activities. The samples taken are Fudai, Taro, and Kamaishi Towns. The three cities are in the same prefecture but suffered different damages. A comprehensive study is therefore essential to illustrate the disaster profile.

RESULTS AND DISCUSSION

Hazard Profile Overview of Iwate Prefecture

The cities of Fudai, Taro, and Kamaishi are all located in the same prefecture, Iwate. However, it is important to note that each area has distinct characteristics. The following map shows the location of the three cities. Previous research has definitively stated that the Fudai City area suffered only minor damage from the Tohoku tsunami. Taro City and Kamaishi City both suffered damage to their city center areas.

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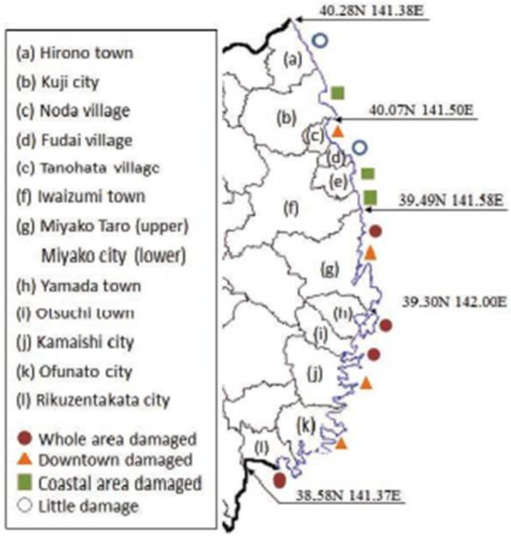

Figure 1. Peta Distribusi Kerusakan pada Prefektur Iwate
Source: Ogasawara, et al., 2012.

In addition to determining the location of the damage caused by the Tohoku tsunami, it is essential to assess each city's specific characteristics. The following assessment of each city's characteristics clearly demonstrates its vulnerability and capacity factors. The study below is an invaluable tool for identifying the risk of the Tohoku tsunami to the three cities.
Display the table as below:

Table 1. Hazard Profile in Iwate Prefecture

Overview		Fudai	Taro	Kamaishi	Reference
Land Characteristics	Topography	Coastal, Mountains & Bays	Bays	Bays	(Nateghi et al., 2016)
	Prefecture	Iwate			
Hazard Characteristics	Earthquake Strength (Magnitude)	4.9	5.0	5.7	(Goto et al., 2019; Ogasawara et al., 2012)
	Run up Tsunami Elevation	17 m	39 m	20.2 m	(Nateghi et al., 2016)
	Damage Impact	light	severe	severe	(Ogasawara et al., 2012)
	Mortality Ratio	1%	3%	7%	
	Damage Ratio	-	60%	70%	
Tsunami Countermeasure	Tsunami breakwater			63 msl	(Uppasri et al., 2013)(Strusińska -correia, 2017)
	Tsunami gates elevation	15,5 m			
	Seawall Elevation	15,5 m	10,5 m		(Nateghi et al., 2016)(Strusińska -correia, 2017)
	Coastal Forest Existence				(Nateghi et al., 2016)
Building	Housing				(Robertson,

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Structure Materials	structure				2015; Uppasri et al., 2013)
	Public building structure	Concrete	Concrete	Concrete	
	Evacuation shelter building structure				
Mitigation Activities	Self-evacuation	Yes	No	Yes	(Lin et al., 2016)
	Education of Mitigation	Yes	Yes	Yes	
	Early Warning System	Yes	Yes	Yes	(Robertson, 2015)

Source: Literature Review

Table 1 clearly shows the disaster profiles of Fudai City, Taro City, and Kamaishi City. However, further studies are required to complete the overall disaster profile. From these profiles, it is clear which variables relate to tsunami disaster mitigation.

Land Characteristics

Fudai City, Taro, and Kamaishi are indisputably part of Iwate Prefecture. Iwate Prefecture is the second largest prefecture in Japan, without a doubt. Iwate Prefecture's northern boundary is Aomori Prefecture. Its southern boundary is Miyagi Prefecture. Iwate Prefecture is located on the coast of Japan and borders the Pacific Ocean. Iwate Prefecture is one of the prefectures most frequently affected by recurrent tsunami disasters.

The topography of the three cities is definitively bay and coastal. All three cities have bays with V-shaped coastlines, as previous research has shown. This topography undoubtedly causes tsunami waves to accumulate in bays, increasing the tsunami height beyond 10 meters. Areas with such topography must prepare structural countermeasures along the Sanriku coast.

Fudai City's topographical characteristics are unique. Unlike Taro City and Kamaishi City, it has both coastal and mountainous areas. Fudai City will have a higher topography than the other two cities. This will undoubtedly improve tsunami disaster mitigation.

Hazard Characteristics

The Tohoku tsunami was a natural disaster that occurred after earthquake activity. The characteristics of the Tohoku earthquake were different from those of previous earthquakes. The Tokohu earthquake had a magnitude of 9.0 with a duration of 20 minutes. This was in contrast to previous earthquakes that had magnitudes of 8.1-8.5. Nevertheless, the Tohoku earthquake produced a smaller amplitude than the previous earthquakes. This may indicate that the intensity of the Tohoku earthquake was lower than the previous earthquake, and caused less structural damage due to the earthquake than by the previous event (Hazarika & Kasama, 2013).

Meanwhile, the aftershock disaster of the 2011 Tohoku earthquake was a tsunami. Although there was no structural damage from the earthquake, tsunami activity with high run-up elevations can damage defence structures in coastal areas. Previous research states that the damage caused by tsunamis is scouring of structural supports, overtopping tsunamis, and tsunami backflow that carries debris (Hazarika & Kasama, 2013; Ogasawara et al., 2012; Prabath et al., 2016).

In terms of tsunami damage ratios, it can be seen that Taro City and Kamaishi City have high damage ratios in comparison to Fudai City. Most of the damage suffered by Taro City and Kamaishi City is concentrated in the center of Koya. Meanwhile, Fudai

City, which has a higher topography, has the lowest tsunami run-up height, so the damage ratio is the lowest among the other two cities. Of course, more research is needed to determine the factors that contributed to Fudai City's success.

Tsunami Structural Countermeasures

1. Tsunami Breakwater

Based on Table 1, the largest breakwater is located in the city of Kamaishi. In addition to Kamaishi City, a breakwater was built in Ofunato City. The breakwater was built to overcome the recurring tsunami disaster. Both cities were inspired by the Meiji Sanriku tsunami that occurred in 1896. At that time, the Meiji Sanriku tsunami had a magnitude of 8.5 magnutudo with a death toll of 21,000 and damage to more than 10,000 houses. The Meiji Sanriku tsunami is considered the worst-case tsunami in Japanese history, before the Tohoku tsunami. The breakwater at Kamaishi is 63 meters deep and is considered the deepest breakwater in the world. The breakwater successfully withstood the Takachi-oki tsunami in 1968. However, it was unsuccessful in the 2011 Tohoku tsunami.

The Tohoku tsunami that occurred was not predicted by the designers. The height of the tsunami exceeded the planned height of the breakwater. As a result, the tsunami severely damaged the breakwater structure and eventually flooded the city. However, the breakwater still mitigated the impact of the tsunami by reducing the height of the tsunami and slowing its arrival time. This gave people additional time to evacuate. Previous research mentioned that without breakwaters, the run-up height would reach 20 m at a speed of 28 m, but due to the presence of breakwaters, the run-up height can be reduced to 10 m with an arrival time of 36 minutes.

The conclusion that can be drawn from the design of the breakwater built in Kamaishi City is that the structural design does not consider the worst-case scenario. The reference tsunami height is the same as that of the previous tsunami. Therefore, when a higher tsunami arrives, the breakwater will not function optimally. In terms of their potential, breakwaters are very effective in minimizing wave run-up height and slowing wave arrival time.

2. Sea Walls

Taro City is one of the cities that uses sea walls to protect the city from tsunami disasters. Taro City is frequently affected by tsunamis. Taro City built seawalls with a height of 10 m, calculated based on the average height of sea water. The seawalls in Taro City were successful in protecting the city from the effects of the Chilean tsunami. However, in 2011, the seawalls built in Taro City did not successfully withstand the Tohoku tsunami. The tsunami surpassed the height of the seawalls, causing the destruction of the structure, and the tsunami flooded the city.

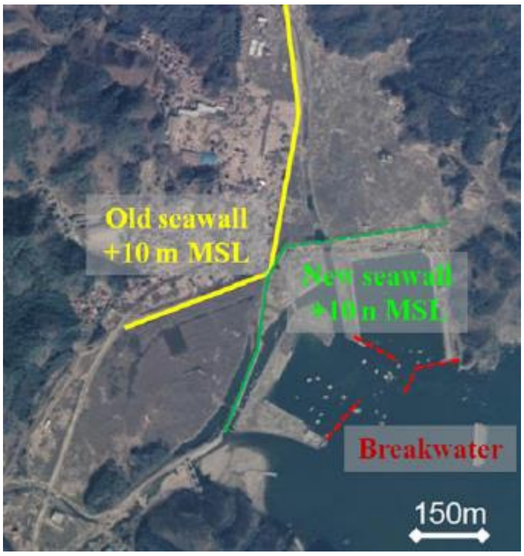

Figure 2. Seawall in Taro City
Source: (Uppasri et al., 2013)

There were three causes for the destruction of the seawalls in Taro City during the Tohoku tsunami. The first cause was the X-shape of the seawalls. This is similar to the topographical shape of the bay, which causes the tsunami energy to concentrate at one point, increasing the height of the tsunami. Another cause was that the soil around the river was not strong enough to support the seawalls. Meanwhile, high, strong currents caused scouring around the foundation and caused the seawall to collapse.

3. Tsunami Gates

Fudai Town is located along the Fudai River. The town has experienced tsunamis caused by tsunamis on the river. The Fudai municipal government built a 15.5-meter-high floodgate in 1984. At that time, the Fudai municipal government was criticized by the public because the investment cost of building a floodgate was very high and considered excessive.

In 2011, Fudai City was a city that successfully responded to the tsunami disaster. Although the Tohoku tsunami that hit Fudai City had a height of 17 m and was overtopped. However, residential areas including evacuation shelters and schools in Fudai City were not affected by the disaster.

4. Coastal Forest

Coastal forests are often the subject of discussion as a means of reducing the impact of tsunamis on urban facilities. Coastal forests are often used as Level 2 protection behind sea walls. Coastal forests that function as protective forests were officially included in disaster risk management in the Japanese government's Forestry Law of 1897. This is because coastal forests can reduce tsunami risk based on the Showa-Sanriku tsunami (1933) and the Chile tsunami (1960).

None of the three cities implemented coastal forests as level 2 protection after the placement of urban protection structures (breakwaters, sea walls). Therefore, when the tsunami overtook the height of the breakwaters, seawalls, and floodgates, it could easily pass directly through the city. However, the provision of coastal protection forests still has its pros and cons, as the coastal forest in Rikuzen-takata, Iwate Prefecture, failed. The forest could not withstand the force of the 20-meter Tohoku tsunami. As a result, many trees were uprooted and became debris in the city. This made matters worse when the debris was carried away by the backwashing tsunami waves, which had more energy to destroy the land-to-sea levee.

Building Structure Materials

Housing Construction - Most of the housing construction in the three cities is wooden. This type of construction is very popular and sought after by the Japanese people. Wood construction is considered earthquake resistant, but it is not resistant to the hydrodynamic forces generated by tsunamis. Wooden houses are highly susceptible to being submerged and washed away by tsunamis. Wooden houses swept away by tsunamis can become floating debris that amplifies the energy of the tsunami wave as it destroys the walls of defensive structures.

Figure 3. Wooden house structures that are easily destroyed and washed away by a tsunami.
Source: (Uppasri et al., 2013)

Public Building Structures - While viewing the three topographies of each town. Taro City and Kamaishi City have the lowest topography. Tall buildings are often used as evacuation areas when there are no mountains or hills nearby. The structures that should be used for such tall buildings are concrete and steel structures. However, the strength of the structure needs to be further studied because the location of Taro and Kamaishi cities, which tend to be bays, can increase the energy from water runoff and wave height. High-rise structures should consider the strength against tsunami hydrodynamic forces, although high-rise buildings minimize the possibility of buildings being submerged by tsunamis.

Preparedness and Mitigation

Fudai City - People remain indifferent to evacuation even though the city has experienced repeated tsunami disasters. They still evacuate the evacuation area even though they are aware of the city's protective structures. The people of Fudai also conduct regular tsunami evacuation drills.

Taro City - The vigilance of the people of Taro City is very low. Although the city has experienced repeated tsunami disasters, the people remain indifferent to evacuation. The people of Taro are the ones who do not heed evacuation warnings. Based on previous data, the community has been warned 4 times. However, people feel safe because there are sea walls protecting the town from the sea. People felt safe because the sea walls in Taro City are 10 meters high and are often nicknamed the Japanese Wall. Contrary to expectations, the 2011 Tohoku tsunami had a height that the seawalls could not withstand. As a result, many people did not have time to evacuate (Parady et al., 2018).

Figure 4. Floating debris trapped 3 storey building structure.
Source: (Robertson, 2015)

Kamaishi City - There was an unforeseen event by the Kamaishi City government. The government did not anticipate that the school and nursing home would be in the flooded area. Only a few teachers and students were able to evacuate to the nearest hill. Others evacuated to the roofs of buildings, but these were destroyed by the tsunami. The lack of evacuation training and simulation for the people of Kamaishi made it difficult for them to evacuate themselves in the event of a tsunami. Therefore, the lesson learned is that there is still a lack of land planning and evacuation knowledge.

CONCLUSION

The success or failure of tsunami disaster management and mitigation implementation is influenced by a number of factors, as evidenced by the 2011 Tohoku tsunami. This is demonstrated by case studies of Fudai City, Taro City, and Kamaishi City. Based on the preceding discussion, it can be concluded that these factors depend on:

1. Topography and land use
2. Hazard Characteristics
3. Structural Mitigation
4. Building Structure
5. Community Preparedness and Mitigation Knowledge.

In general, these factors can be classified into three categories: prevention, mitigation, and preparedness. The following lessons can be derived from these cities:

1. Cities situated in bays should maintain a high level of vigilance, as the susceptibility to tsunami impacts is amplified in these regions. For instance, the energy accumulated within the bay will be greater, resulting in an increase in the height of the tsunami.
2. Structural mitigation planning should take into account the most adverse potential outcome. This approach is exemplified in the planning of tsunami gates in Fudai City, where the design criteria have been augmented in light of historical data. In contrast, Taro City and Kamaishi City did not augment the structural criteria and standards in consideration of previous events. Consequently, the implementation of structural mitigation cannot be optimized in the event of a larger disaster.
3. It is recommended that building codes be revised to require the use of appropriate building structures in coastal areas that can withstand the hydrodynamic forces of water. The structure can be constructed using recommended structural materials, such as concrete, in order to ensure that the building is not submerged. Additionally, consideration should be given to the floor height in order to withstand the hydrodynamic forces of water.
4. In order to ensure the most accurate assessment of potential inundation areas, it is essential to utilize the most extreme scenario in zoning planning. This phenomenon

can be observed in the case of Kamaishi City, where the worst-case scenario was not applied, resulting in urban areas that had been designated as safe but were inundated by the Tohoku tsunami. In contrast, the urban areas of Fudai City were situated on elevated terrain and did not include any residential or commercial developments within the designated inundation zone. Consequently, upon the tsunami exceeding the height of the tsunami gate, the resulting tsunami runoff did not result in damage to the city center..

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