

PROTECTIVE EFFECT OF COASTAL LEVEES AGAINST THE MEGA-TSUNAMI OFF THE PACIFIC COAST OF TOHOKU CAUSED BY THE 2011 EARTHQUAKE

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Abstract: On 11 March 2011, a mega-tsunami caused by the 2011 off the Pacific coast of Tohoku Earthquake destroyed most of the coastal levees along the Pacific coast of northeastern Japan. These coastal levees were constructed in response to previous tsunamis and storm surges. The life-saving effect of coastal levees was examined by comparing on-site observation data from this tsunami with records of the Showa Sanriku Tsunami (1933). To compare human fatalities among coastal towns, the fatality rate was defined as the sum of the number of fatalities and missing persons as a proportion of a town's population. Examining the relationships between the fatality rate, the tsunami inundation height, and the existence of coastal levees for the different tsunamis revealed markedly different outcomes in terms of the number of fatalities associated with a tsunami inundation height. As a result, at a tsunami inundation height of 10 m the Showa Sanriku Tsunami's fatality rate reached 3 to 90%, while that associated with the off the Pacific coast Tohoku Earthquake Tsunami's was only 1 to 3%. Since the coastal levees were mainly built after the Showa Sanriku Tsunami, it is cleared that one of the factors that contributed to a decrease in the fatality rate was the protective effect of the coastal levees against inundation by tsunamis.

1. The 2011 off the Pacific coast of Tohoku Earthquake and Tsunami

The M9 earthquake, named the "2011 off the Pacific coast of Tohoku Earthquake" by the Japan Meteorological Agency, which originated off the northeastern coast of the Japanese mainland in the Pacific Ocean on 11 March 2011, caused extensive damage to the Tohoku Sanriku Region. The associated tsunami, which had a maximum run-up height of 37.9 m at Iwate-Miyako, caused numerous casualties and extensive damage to property in Iwate, Miyagi and Fukushima prefectures. Elsewhere along the coast, such as at Iwate-Ofunato and Miyagi-Onagawa, the run-up heights of the tsunami reached 29.6 m and 18.4 m, respectively. In these prefectures, the tsunami either destroyed or severely damaged numerous breakwaters, tidal embankments, coastal levees, and coastal towns in the Iwate, Miyagi, and Fukushima prefectures. In addition, as a result of the earthquake and associated tsunami, 15,854 people died, 3,155 went missing, 26,992 were injured, approximately 470,000 were displaced, and at least 383,246 buildings were either destroyed or damaged.

2. History of restoration following natural coastal disasters in the Tohoku Sanriku Region

Several large offshore earthquakes have occurred previously in the same geographic region, including the Keicho Sanriku Earthquake in 1611, the Meiji Sanriku Earthquake in 1896, and the Showa Sanriku Earthquake in 1933. Each of these events was associated with devastating tsunamis along the Sanriku Coast of the northeastern Pacific Ocean in Japan. The coastline of this area is particularly vulnerable to tsunami events, because it is composed of numerous V-shaped bays (saw-tooth coastline) that open toward the ocean; the effect of this V-shape is that it amplifies the effect of incoming tsunamis or surge waters. The M7.6 earthquake of 1896 produced tsunamis as high as 38 m, and the M8.6 earthquake along the Sanriku coast in 1933 produced tsunamis as high as 29 m and caused 3,064 fatalities. In 1960, the Chilean Earthquake Tsunami was propagated across the Pacific Ocean and hit the Sanriku coast. In addition, storm surges have occasionally caused extensive damage along the southern Sendai coast. Many of the breakwaters, tidal embankments and coastal levees along the Sanriku coast have been destroyed or severely

damaged by these large earthquakes, tsunamis and storm surges, and many of these structures have been reinforced or restored throughout the long term.

Most of these coastal embankments and levees were destroyed by the tsunami associated with the 2011 off the Pacific coast of Tohoku Earthquake. Fig. 1 shows the alongshore height of the previous coastal levees, i.e. the heights of the coastal levees before the earthquake, as well as the tsunami inundation height and the fatality rates of areas extending from the Kuji coast in Aomori in the north to the south coast of Sendai Bay in Miyagi to the south. In this figure, the fatality rate is defined as the sum of the number of fatalities and missing persons as a proportion of a town's population. The figure shows that tsunami height, fatality rate, previous levee height, and the planned levee height differ markedly between areas. Since the relationships between these difference parameters are not clear and cannot be inferred from the figure, we intend to investigate these aspects in a future study.

According to a survey by the Japanese newspaper, Asahi Shimbun, restoration plans for new coastal levees have been drafted by Iwate and Miyagi prefectural governments, but reconstruction work is only expected to be undertaken on 18 km of the 190 km damaged levees in Iwate, Miyagi and Fukushima prefectures. The survey found that many residents oppose the construction of higher levees, as the higher structures may obstruct their views of the sea or prevent them from sighting future tsunami invasions. Moreover, by limiting visibility of the ocean, it is considered that the coastal levees may adversely affect the ability of local residents to read the condition of the sea by observing wave patterns. Because residents have yet to reach consensus on the proposed reconstruction plans, we need to illustrate the scientific basis upon which the coastal levees could prevent fatalities in the even of future tsunamis.

3. Life-saving effects of coastal levees

Regarding the tsunami that followed the Showa Sanriku Earthquake in 1933, Watanabe (1985) examined the tsunami inundation height, number of fatalities, and population of each of the affected coastal towns in Iwate Prefecture, it is not clear whether the number of fatalities in that study included the number of people who went missing.

In addition, the coastal levees that existed in 1933 are considered to have been insufficient or non-existent, because Watanabe's report did not describe any coastal levees along the Iwate coast in that report. We compared Watanabe's 1933 tsunami data with the data from the 2011 off the Pacific coast of Tohoku Earthquake Tsunami. Specifically, we examined the life-saving effect associated with the coastal levees by examining the relationship between the fatality rate and the tsunami inundation height (Fig. 2). Using Watanabe's data, the fatality rate was defined as the ratio of the number of fatalities to the population of a coastal town. For the Meiji Sanriku Tsunami, Fig. 2 also shows the scattered data-range by 'x--M.Iwate--x' mark for Iwate prefecture, and by 'x---M.Miyagi--x' mark for Miyagi prefecture, respectively. The figure also shows the trend (two dashed lines) between fatalities and tsunami height reported by Kawata (2011).

Since Watanabe's (1985) survey data was restricted to Iwate, we only examined the relationship between the fatality rate and tsunami inundation height for the 2011 off the Pacific coast of Tohoku Earthquake and the areas in Iwate (Fig. 2). Data is shown for following points on the figure: areas where coastal levees exist along the coastline (\square); coastal levee and coastal town on middle-high ground (\square); coastal levees and coastal towns on high ground (\square); coastal levees and the existence of tsunami breakwaters present in bay mouths (\square). Points indicated by 'Fs' and 'FH' show data from the Iwate-Fudai village obtained during the Showa Sanriku Tsunami and the 2011 off the Pacific coast Tohoku Earthquake Tsunami, respectively. "High ground" refers to towns located above the tsunami run-up height. "Middle-high ground" refers to towns located between sea level and the tsunami run-up height.

The ranges in fatality rates at different inundation height for the for the Showa sanriku Tsunami and the most recent tsunami are shown by the dashed and solid lines in Fig.2, respectively. While the fatality rates in Fudai village (Fs), reached levels as high as 98% in the Showa Sanriku Tsunami, these values decreased to 0.03% in the most recent tsunami (FH). In other words, fatality rates in Fudai village at the time of the Showa Sanriku Tsunami, fatality rates in the Fudai village were as high as 98% when the tsunami

inundation height was 8 to 13 m, and as low as 0.03% in the most recent tsunami when inundation height was 18.5m.

One of the reasons for the marked differences in the ranges of the tsunami inundation heights (i.e. 2-6m and 11-24m) at a fatality rate of 1% is considered to be due to the effect of the concrete coastal levees that were constructed after the Showa Sanriku Tsunami. Indeed, this difference in the ranges of these variables is considered to reflect the life-saving effect of the coastal levees. Of course, the observed life-saving effects cannot be attributed entirely to the existence of hard countermeasures, as soft countermeasures, such as tsunami warnings, drills and evacuation procedures, and the difference between night (Showa Sanriku Tsunami) and day (the most recent tsunami) are also very important.

4. Conclusions

The life-saving effect of coastal levees was assessed by comparing data from the Showa Sanriku Tsunami (1933) and the 2011 off the Pacific coast of Tohoku Earthquake Tsunami. Importantly, while the life-saving effects reported in this study were likely due to a combination of both hard and soft countermeasures, the results of this study can be summarized as follows:

1) Alongshore variations in levee height are related to the history of previous restoration efforts that focused on repairing damage due to tsunamis and storm surges in each area. The fatality rates in each area were not only related to the effect of coastal levee height, but also due to a variety of other factors.

2) Using a diagram to show the relationship between the fatality rate, tsunami height, and the existence of coastal levees, a tsunami inundation height of 15 m was associated with a fatality rate of 10-90% in the Showa Sanriku Tsunami. However, these rates decreased to less than approximately 10% after the most recent tsunami.

3) In the most recent tsunami the existence of coastal levees had a great effect on saving lives by comparing the Showa Sanriku Tsunami, i.e. for a fatality rate of 1%, the tsunami inundation height would have been as low as 3-8m at the time of the Showa Sanriku Tsunami vs. 11-24 m for the tsunami following the 2011 off the Pacific coast of Tohoku Earthquake.

References

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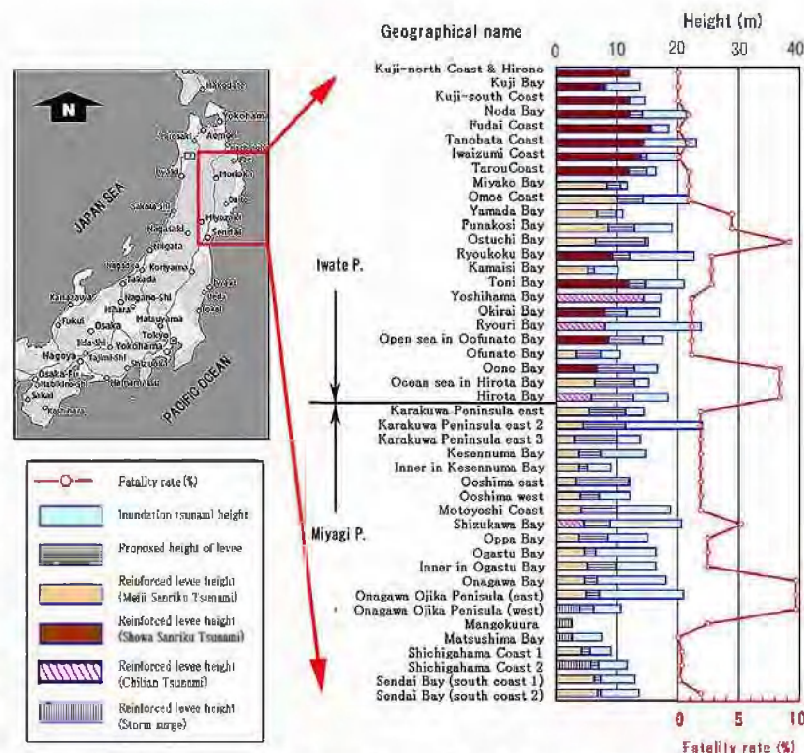


Fig.1 Alongshore distribution of previous coastal levee height, proposed levee height, tsunami inundation height, and fatality rate due to the 2011 off the Pacific coast of Tohoku Earthquake Tsunami between the Kuji coast and Hirono in Aomori in the north and Sendai Bay in Miyagi in the south.

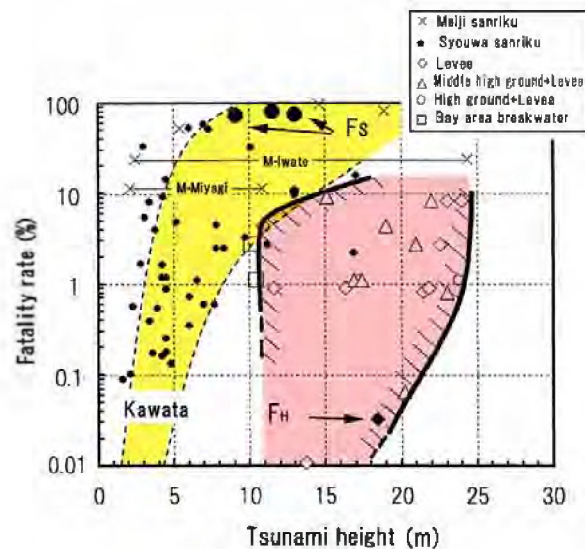


Fig. 2 Comparison of the Showa Sanriku Tsunami (yellow area) and the 2011 off the Pacific coast Tohoku Earthquake Tsunami (pink area), and the life-saving effect of the coastal levees. Dashed lines show the ranges indicated by Kawata (2011) based on records from the Meiji Sanriku Tsunami, the Showa Sanriku Tsunami, the Thorankai Tsunami, the Nankai Tsunami, the Okushiri Tsunami Generated by Southwest-off Hokkaido Earthquake, and the Flores Island Tsunami in Indonesia.