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Consideration for effective height of sea walls against tsunami

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Tsunami wave height data at several sites in Tohoku district in Japan were examined and an empirical extreme value distribution with both upper and lower bounds was applied to model the cumulative probability distribution function of annual maximum wave height. Then by estimating the construction cost of sea walls against the tsunami and the expected damage cost due to a tsunami attack, the expected total cost was studied. Observation of the tendency of expected total cost with the design height of a sea wall indicates that sea wall construction is not economically justified, unless the height exceeds the upper bound of tsunami wave height.

Keywords: tsunamis; evacuation scenarios; sea walls; extreme value distribution; total expected cost

1. Introduction

Off the Pacific coast, the Tohoku Earthquake caused outrageous tsunami damages to many cities and towns on the Pacific coast of Tohoku and Kanto districts in Japan on 11 March 2011. Only a few sea walls prevented the tsunami but most sea walls were flowed over by tsunami waves. In many areas of the sea coast the highest wave in history was recorded. The height of the sea wall was not enough to prevent the tsunami at this time. The government made a general guideline for sea wall construction but the sufficient information for the appropriate design height of sea walls has not been sufficiently provided for discussions. Some fishing villages prefer the natural coast without a high sea wall for their daily lives. Such discussions have not been encouraged until recently.

The government suggested to determine the height of sea wall that prevents the level one tsunami wave in order to protect whole properties within the wall, but cannot prevent the maximum level two tsunami wave. The definition of level one and level two may be given in terms of the return period as 100 years and 500 years respectively, although the probabilistic model for tsunami wave height has not been quantitatively discussed. We have to accept the low probability of exceedance of tsunami, even after the construction of sea walls. Evacuation scenarios must be simulated and practiced for tsunamis greater than the sea wall height. Nevertheless, the sea wall construction is still expensive and may not be economically affordable. At the same time, a tall sea wall may destroy the beautiful natural landscape.

Sea wall constructions against tsunami have been carried out since late 1970s for the Pacific sea coast in Tohoku district in Japan. For example sea walls at Taro were constructed in 1979. One of the tallest water gate in Fudai was constructed in 1984. Sea walls at Tohni Kojirahama were constructed in 1990. Heights of sea walls at several typical coasts are listed in Table 1 to provide general information for tsunami sea walls. Nine coasts in Iwate prefecture, two coasts in Miyagi prefecture and two coasts in Fukushima prefecture are selected. Heights before the earthquake in 2011 and heights as planned for recovery construction projects are both shown together with estimated tsunami wave heights. These height data are available in the web site of Architectural Institute of Japan (AIJ, https://www.aij.or.jp/jpn/databox/2012/20111115.pdf, 2014).

The occurrence of earthquakes that causes the tsunami is rather infrequent, but the Sanriku sea coast, the pacific coast of Tohoku district, was attacked by huge tsunamis at least five times during 150 years. Then the probabilistic model for the tsunami wave height can be proposed by utilising some records of the tsunami in the past. The total expected cost, which includes the construction cost of sea wall and the expected damage cost, can be examined based on the probabilistic model of a tsunami. The effective height of a sea wall against tsunami can be discussed by examining the total expected cost. Numerical examples are based on a very approximate assumption of construction cost and damage cost but results may be applied to general situations in order to share comments on the necessity of sea walls among stakeholders.

Table 1. Height of tsunami sea walls in three prefectures in Tohoku district.

Coast	Height existing (m)	Height as a plan (m)	Tsunami wave (m)
Kuji south	12.0	12.0	14.5
Fudai	15.5	15.5	18.4
Taro	10.0–13.7	14.7	16.3
Miyako	8.0–8.5	10.4	11.8
Yamada	6.6	9.7	10.9
Ohtsuchi	6.4	14.5	15.1
Tohni	11.8	14.5	21.0
Yoshihama	14.3	14.3	17.2
Hirota	4.95–6.5	12.5	18.3
Karakuwa east	4.5–6.1	11.3	14.4
Onagawa	3.2–5.8	6.6	18.0
Souma	6.2	7.2	8.7–14.5
Nakoso	6.2	7.2	7.7

2. Application of extreme value distribution model to tsunami wave heights

Four sites in Sanriku coast are selected for an extreme value model study of tsunami wave heights. Four sets of tsunami wave height data in Sanriku coastal area are extensively available in a new version of Comprehensive List of Destructive Earthquakes in Japan (Usami et al., 2013), which was originally edited by Professor Usami and now revised by including most recent data. Tsunami wave height distribution for Ansei earthquake 1856 was also provided in the same reference but only a description as 3.6–3.9 m is available for the whole Sanriku coast. Then, five tsunami wave heights data can be listed in Table 2.

Three sites: Taro, Yamada and Tohni Kojirahama are all in Iwate prefecture and Ogatsu is in Miyagi Prefecture. A location map for these sites is shown in Figure 1. All sites are fishing villages and were attacked by tsunamis causing serious damages. No destructive earthquakes were reported in north Tohoku district between 1800 and 1856, then tsunami wave heights in Table 1 can be regarded as top five annual maximum wave heights during 200 years. The variation of tsunami heights seems to be caused by the type of earthquakes and also the geographical conditions of the sea coast. It is interesting to note that the order of tsunami heights is not always the same.

Table 2. Recorded tsunami wave heights (m) for five earthquakes for four sites in Sanriku coast.

	Taro	Yamada	Kojirahama	Ogatsu
Higashi Nihon 2011	29.9	10.1	17.4	15.3
Chile earthquake 1960	2.6	3.3	4	3.9
Showa Sanriku 1933	10.1	4.5	6	4.5
Meiji Sanriku 1886	14.6	5.5	16.7	3.1
Ansei 1856	3.6	3.6	3.6	3.6

An empirical extreme value distribution model proposed by the author is originally intended to represent a distribution model for the annual maximum earthquake ground motion, but the occurrence nature of extreme value of ground motion intensity is rather similar to the tsunami height as only a few annual maxima are significant for a period of 100 years or so and also the existence of upper bound value provides more realistic distributions. The empirical extreme value distribution with both upper and lower bounds may be written as (Kanda, 1994):

$$F(x) = \exp\left[-\left(\frac{w-x}{ux}\right)^k\right] \quad (1)$$

where w is the upper bound value and u and $k$are the scale and shape parameters respectively.

Fitting of Equation (1) to the data in Table 1 is attempted on the Gumbel probability paper with the Hazen plots. Figures 2–5 illustrate satisfactory extreme value models for the annual maximum tsunami height at different locations. The assumption for the upper bound value is rather arbitrary however the Frechet distribution, which has no upper bound, seems to lead to a rather unlikely high value at the range of return period of 1000 years or over and some assumption for the upper bound value will be more realistic. Since the number of significant tsunami data is limited for even a rather long period such as 200 years, this situation would not be improved in the near future. Local geographical effects are also expected to be significant, and it would not be easier to find any consistent correspondence between locations and the upper bound values.

3. Total expected cost study for the design height of sea wall against tsunami

3.1. *Basic formula*

The minimisation of total expected cost, which includes the initial construction cost and expected failure cost, has been widely applied for the determination of design loads (Kanda & Ellingwood, 1991). Numerical studies were conducted for two sites, i.e., Yamada and Kojirahama. The total cost can be written as:

$$C_T = C_I + \sum_i \Delta P_{fi} C_{fi}. \quad (2)$$

where ΔP_{fi} is the increment of probability of exceedance for the assumed service life of 100 years at the tsunami height level i. The probability of exceedance for 100 years is derived from the annual probability model defined by Equation (1) with appropriate parameters for each site. The construction cost, C_I, will depend on the height and length of the sea wall. By considering the construction cost \$10 million for the sea wall in Kojirahama with the height

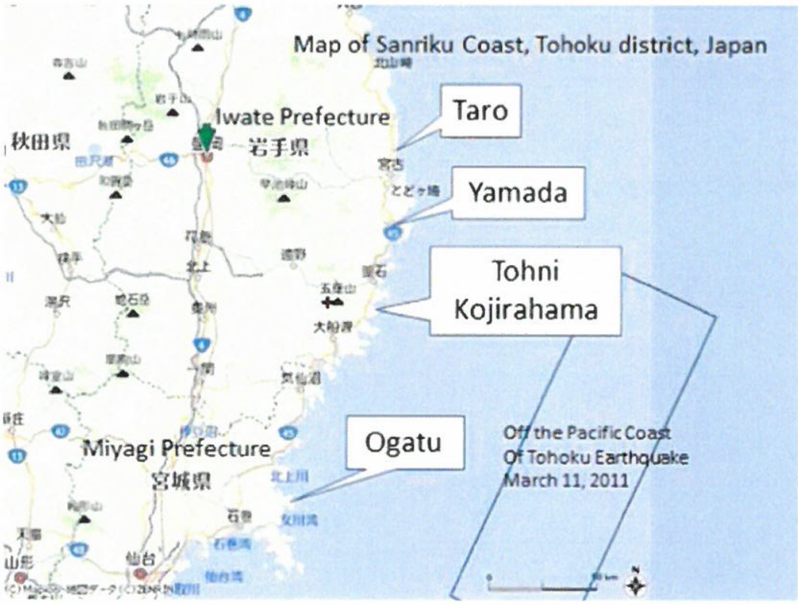

Figure 1. Map of Sanriku coast, Tohoku district, Japan.

12.5 m and the length 420 m in 1990, the assumption was made as, $10 million for the height 4 m and $50 million for the height 20 m and with a linear increase in between. The same assumption was used for both sites.

3.2. *Case studies for fishing villages on the Sanriku coast in Japan*

The cost estimate for the damage, C_f, will depend on the distribution of developed area of the low altitude. Damages caused by the tsunami on 11 March 2011 at Kojirahama were reported as that 116 houses were collapsed or lost and 23 houses were seriously damaged among 415 houses (Kanda et al., 2011). Two persons died while the population was 641. Although the geographical condition and urbanisation is rather different for individual sites, by considering the damage at Kojirahama caused by Off the Pacific coast of Tohoku Earthquake the assumption was made as follows: $5 million when a 4 m wave attacks and $45 million when a 20 m wave attacks with linear interpolation and extrapolation. Again the same assumption was used for both sites. As a hypothetical situation, a constant damage cost of $50 million was introduced to examine the influence of damage cost on the tendency of total expected cost.

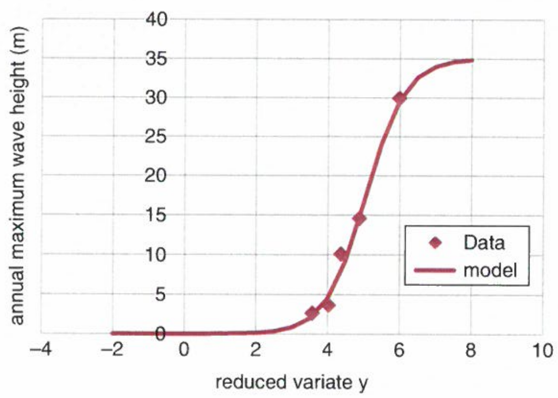

Figure 2. Extreme value model for tsunami wave height at Taro, Iwate, Japan, with $w = 35$, $u = 10000$ and $k = 0.55$ for Equation (1).

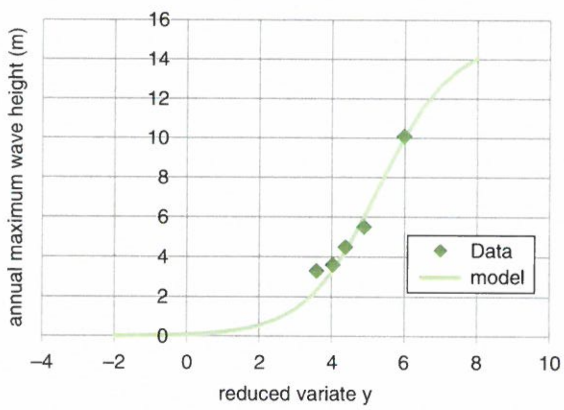

Figure 3. Extreme value model for tsunami wave height at Yamada, Iwate, Japan, with $w = 15$, $u = 200$ and $k = 1.0$ for Equation (1).

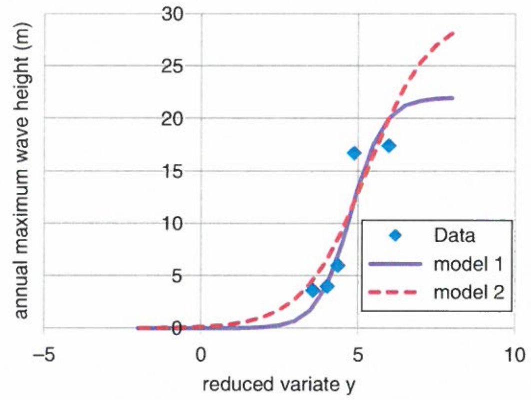

Figure 4. Extreme value model for tsunami wave height at Tohni Kojirahama, Iwate, Japan; model 1 with $w = 22$, $u = 10000$ and $k = 0.52$ and model 2 with $w = 30$, $u = 200$ and $k = 1.0$ for Equation (1).

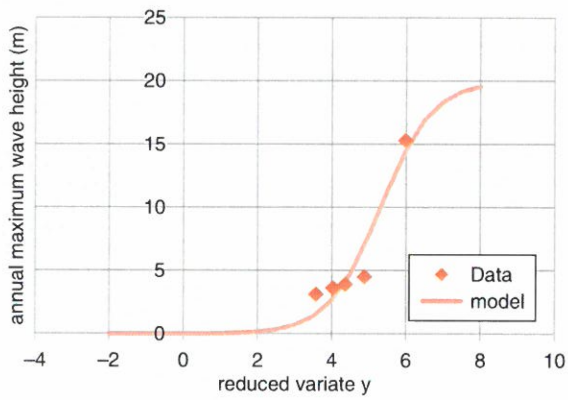

Figure 5. Extreme value model for tsunami wave height at Ogatsu, Miyagi, Japan, with $w = 20$, $u = 2000$ and $k = 0.7$ for Equation (1).

The results are shown in Figure 6 for Yamada and Figure 7 for Kojirahama. Both total cost and expected damage cost for the hypothetical constant damage case are shown in dotted lines in Figures 6 and 7 by indicating total 2 and Pf × Cf 2 in the legend. Since a feature of the tail of the extreme value model is different, the failure cost tendency with the design wall height is different. Nevertheless there is no minimum value except at the height of upper bound assumption. Results indicated that unless the height of the sea wall exceeds the upper bound tsunami wave height, the construction of a sea wall seems not to be economically justified. By also considering the influences on the landscape, it will not be a wise decision to construct the sea wall with a height around 15 m, which was reported as the decision of Iwate prefecture. Sea wall construction projects are financed by the government.

When the expected total cost study is applied to the determination of earthquake load for a building, the cost-up ratio of building construction against the intensity of earthquake ground motion is extremely low in comparison with the cost-up ratio of sea wall construction against the tsunami. The failure cost for the collapse of a building will not vary with the intensity of motion but the damage caused by tsunami generally increases with the height of tsunami, as the higher wave can reach the higher altitude area. An optimal design point can be obtained as the minimum of the total expected cost for ordinary structural design cases of buildings, but it does not apply for the case of a tsunami sea wall. Only the hypothetical case of constant damage cost for Yamada shows the minimum of total expected cost in Figure 6, but it is rather unlikely in real situations.

We could pay attention to the assumption of upper bound value for the wave height. It is not possible to provide any scientific evidence for the upper bound value. However it does not change the tendency of total expected

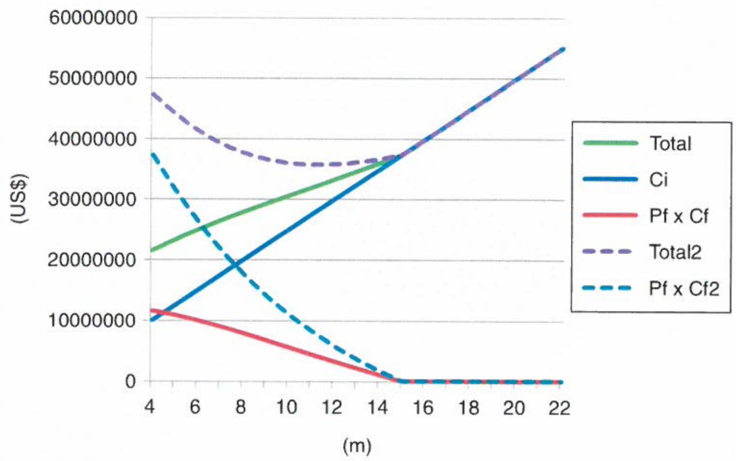

Figure 6. Total expected cost study with sea wall height at Yamada, Iwate, Japan.

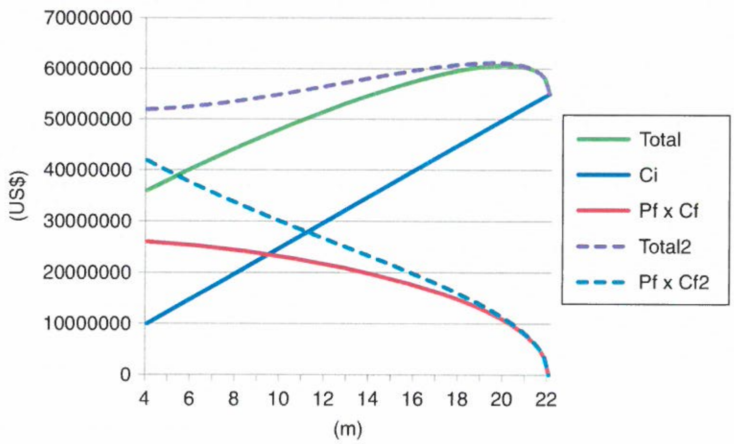

Figure 7. Total expected cost study with sea wall height at Tohni Kojirahama, Iwate, Japan.

cost with the sea wall height and so we can regard the estimation of upper bound value as being not significant. For decision-making, we should consider the high uncertainty of the upper bound value for the extreme value distribution, but the nature of tendency of total expected cost found in this study will apply to all cites with possible tsunami damages.

3.3. *Alternative cases with various models*

Alternative models for the initial cost and the damage cost are introduced for comparison. A similar study to discuss the height of sea wall on a probabilistic model of tsunami wave height was conducted for Rikuzen-Takada city by a research group (Kono et al. 2013). An exponential curve for initial construction cost was assumed for a rather wider area of possible tsunami inundation to conclude an optimum sea wall height as 10 m. A comparable model was examined with a similar initial cost model, designated as Initial 2 and damage cost estimation model as \$10 million at 4 m wave attack and \$100 million at 20 m wave attack as designated as Pf × Cf 2, which are doubled damage costs from the original model in Figure 7 for Kojirahama. A tsunami extreme value model with the upper bound of 30 m was used. Results are shown in Figure 8 and an optimal height is observed around 13 m. When a wide area has to be considered, a high sea wall could be justified from cost benefit considerations, but it may not apply for fishing villages on the Sanriku coast where a steep slope goes down into the sea as known as the saw-toothed coastline.

Another consideration can be made for a realistic situation for Kojirahama, where a part of a sea wall was damaged. The prefecture has suggested to increase the height from 12.5 to 14.5 m. The initial construction cost model was reduced to 1/7 until 12.5 m as only the damaged portion is

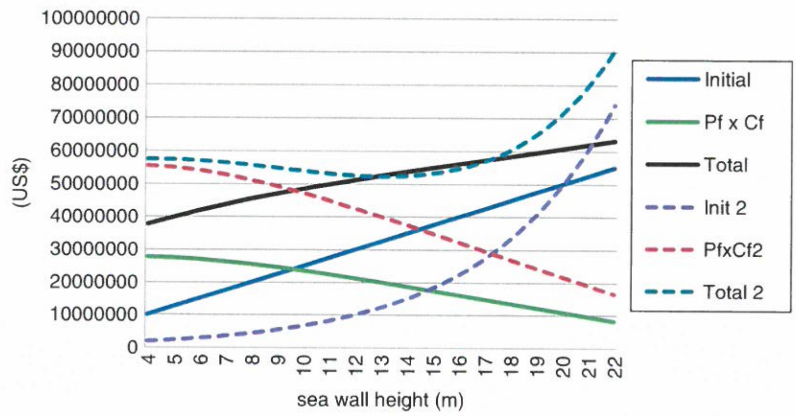

Figure 8. Total expected cost study with sea wall height with another model for initial cost and damage costs at Tohni Kojirahama, Iwate, Japan.

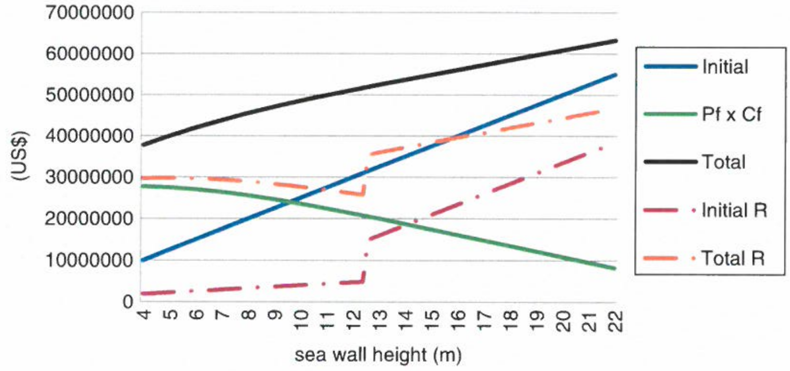

Figure 9. Total expected cost study with sea wall height for comparison with new construction and restoration cases at Tohni Kojirahama, Iwate, Japan.

reconstructed then linearly increases as the original case. Obviously the optimum height is 12.5 m, which requires only the restoration but no increase of the height as shown in Figure 9. Only a few metres of increase may not reduce the possibility of tsunami attack. The probability of occurrence of tsunami wave height between 12.5 and 14.5 m is very low, while the construction cost dramatically increases for the height greater than 12.5 m (Figure 9).

4. Conclusions

An empirical extreme value distribution with lower and upper bound values can be successfully applied to model the annual maximum tsunami wave height for several sites in the Sanriku coast, Tohoku district in Japan. Then, a total expected cost study was conducted to examine the effectiveness of the sea wall height for most fishing villages and it was found that the sea wall construction may not be economically justified unless the sea wall height exceeds the upper bound of tsunami wave height which seems not practicable. The appropriateness of sea wall height is not only the engineering and economic problems but also the landscape aspect as well as the ecological effects have to be considered. This article concluded rather negative aspects for the sea wall construction against tsunami, but wide range of discussions would be necessary for people who live near the sea coast where future tsunami attacks are definitely expected.

Disclosure statement

No potential conflict of interest was reported by the author.

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