HISTORICAL TSUNAMI HEIGHTS ALONG THE COAST OF SHIKOKU ISLAND IN JAPAN

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ABSTRACT

The coasts facing the Pacific Ocean around Shikoku island in Japan have been attacked by huge tsunamis at intervals of 100-150 years. These tsunamis have inflicted severe damage on human lives and houses in towns and villages along the coast. In order to clarify tsunami characteristics, old data on the heights of four big historical tsunamis along the Shikoku coast have been re-examined. New data, including the inundation heights of three of the historical tsunamis, have been compared with those of the fourth, the 1946 tsunami.

Then, the inundation heights of these historical tsunamis were compared with the values calculated by numerical simulations and the tsunami heights of the 1854 tsunami reproduced using the data of the 1946 tsunami.

INTRODUCTION

The oldest tsunami recorded in a historical document in Japan occurred in 684 and since then many tsunamis have been recorded in historical documents. Figure 1 shows a tsunami map in Japan. The circles show the historical epicenters of earthquakes generated in the sea region near the Japanese coast which caused tsunamis. The size of each circle expresses the tsunami scale or tsunami magnitude m. The coasts facing the Pacific Ocean around Shikoku island in Japan have been attacked by huge tsunamis at intervals of 100-150 years. These tsunamis have inflicted severe damage on human lives and houses in towns and villages along the coast.

First, data on four big historical tsunamis along the Shikoku coast were re-examined in detail in addition to informations of old documents discovered in the recent several years. The tsunamis chosen as the subject of this study are as follows; the Keicyo tsunami on February 3, 1605 (tsunami magnitude m=3, death toll about 2,500 on Shikoku island), the Hoei tsunami on October 28, 1707 (m=4, death toll about 2,800 in Kochi Prefecture), the Ansei Nankai tsunami of December 24, 1854 (m=4, death tolls about 380 in Kochi, and 90 in Tokushima Prefectures) and the Showa Nankai tsunami on December 21, 1946 (m=3, death toll about 1,300 in Japan).

Second, the inundation heights of three historical tsunamis were compared with those of the 1946 tsunami at a location where the tsunami data had been recorded along the Shikoku coast. Although the tsunamis attacked the same stretch of coast, there are some locations where the tsunami heights are extremely different in size. Numerical simulations for three of these tsunamis except the 1605 event were carried out in order to consider the reason why the tsunami heights at a certain limited location had been amplified.

Furthermore, the inundation heights of the 1854 tsunami were estimated by using the calculated and observed values of the 1946 tsunami.

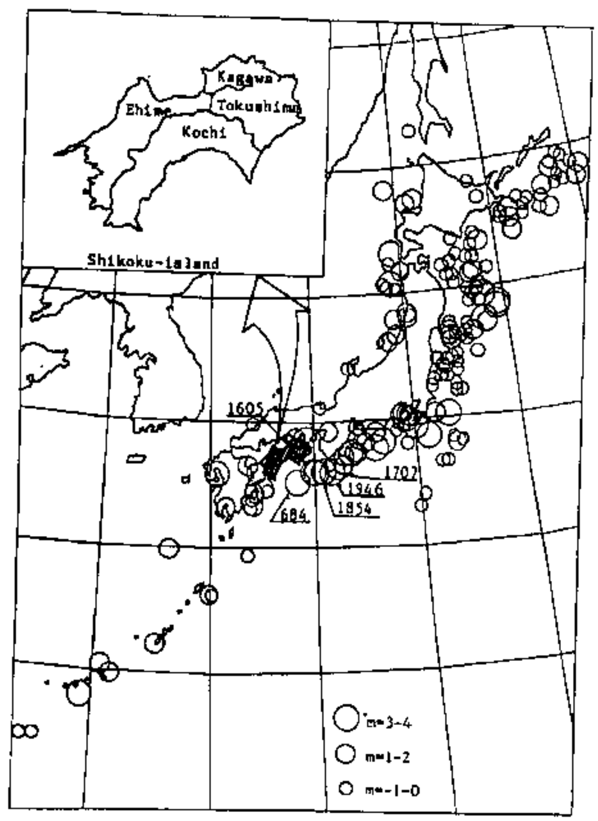

Figure 1. Epicenters of earthquake and tsunami magnitude

THE FOUR HISTORICAL TSUNAMIS ALONG THE SHIKOKU COAST

Details of these tsunamis recorded in historical documents are available for the analysis of tsunamis occurring along the Shikoku coast. We made field surveys along the coast in order to check inundation height which some researchers had surveyed but not in sufficient accuracy. At first, the data of these four tsunamis were checked by surveying obscure inundation heights that had been obtained from historical documents by several researchers and the newly discovered tsunami data from the historical documents were added to the existing data.

Damages along the Shikoku Coast Caused by the Four Historical Tsunamis

Many records of these tsunamis along the Kochi and Tokushima coasts, which lie near tsunami sources have been well recorded in historical documents but there are few records of tsunamis occurring along the Ehime and Kagawa coasts which are located in the Seto Inland Sea.

Figure 2 shows the towns and villages where severe damage was inflicted by the four historical tsunamis.

Figure 2. Towns and villages inflicted by severe damage

There were only few data in historical documents about the 1605 tsunami along the Shikoku coast. However, it is estimated from historical documents that this tsunami was very big. The inundation heights at Sakihama fishery harbor and Kannoura in Kochi reached 9.5m and 5.5m and the numbers of deaths were 50 and 350, respectively. At Shisikui in Tokushima, the inundation height reached 5.5m and 1500 people were killed.

In the case of the 1707 tsunami, the tsunami height at Usa bay in Kochi reached 8m and 400 people were killed. At Asakawa in Tokushima, the inundation height was 6.5m and 170 people were killed.

The inundation height of the 1854 tsunami was 7.5m at Usa, 7.5m at Kamikawaguchi in Kochi and 6.5m at Yuki bay and at Asakawa in Tokushima.

Figure 3 shows the inundation heights of the 1946 tsunami around Shikoku island. The vertical axis in this figure indicates the inundation height above the mean sea level. The data of the 1946 tsunami are large in number and would be the most reliable for inundation heights. The tsunami heights in the western part of the Kochi coast were relatively higher than those in the eastern part. The tsunami height in Nomi bay reached 5.2m. Along the Tokushima coast, the maximum tsunami height reached 4.88m in Asakawa bay and 85 lives were lost there. The tsunami heights depend largely on the location and the heights have been comparatively high along the Kochi coast and the southern part of the Tokushima coast. On the other hand, the Ehime and Kagawa coasts located in the Seto Inland Sea have suffered less damage.

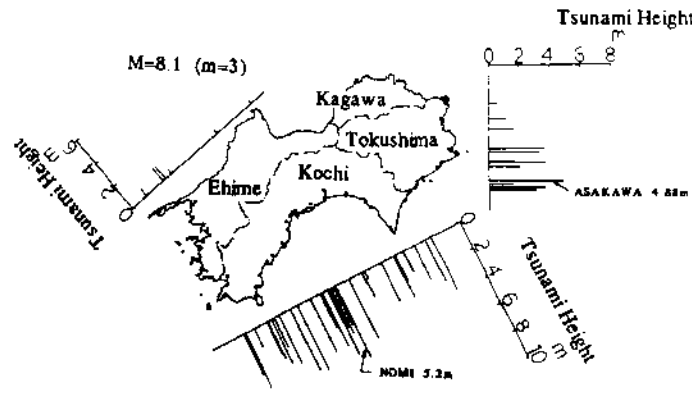

Figure 3. Inundation heights of the 1946 tsunami around Shikoku island

The Comparison of the Four Historical Tsunami Heights

The inundation heights of three historical tsunamis were compared with those of the 1946 tsunami at a location where tsunami data had been recorded along the Shikoku coast (Figure 4). The vertical axis in Figure 4 indicates the ratio R of the tsunami heights of three historical tsunamis to the 1946 tsunami heights. The inundation heights of the 1854 tsunami, the 1707 tsunami and the 1605 tsunami are 1.2-3, 1.2-3.6 and 1-4.6 times as large as those of the 1946 tsunami, respectively. We can see there are some locations where the tsunami heights are extremely huge in comparison to the neighboring villages.

THE NUMERICAL SIMULATIONS FOR THE HISTORICAL TSUNAMIS

The numerical simulation for the general standard of the Nankai Region tsunami is based on an assumption that the sea water surface is still at the beginning and that a tsunami is generated as a given sea surface elevation equal to the vertical displacement of the sea bed by the earthquake. At first the parameters of a fault model were given. Then the final displacement of the sea bed was calculated by the formulation of Mansinha and Smylie (1971). It is supposed that the vertical displacement of the sea bed is linearly increased and completed within a previously appointed time. The fault models used in this numerical simulation are Aida's models (1981) as shown in Table 1.

Table 1. Fault models proposed by Aida (1981)

Tsunami (Model)		L (km)	w (km)	δ (°)	φ (°)	z (km)	us (m)	ud (m)	τ (min)	Mo (dyne-cm)
1946 NANKAI (Model 19')	E part	150	70	10	N20W	10	2.4	3.2	0.5	6×10^{28}
	W part	120	120	20	N20W	1	1.2	4.8	3-10	
1854 ANSEI (Model 20')	E part	150	70	10	N20W	10	2.8	3.7	0.5	8×10^{28}
	W part	150	120	20	N20W	1	2.8	5.6	0.5	
1707 HOEI (Model 29')	E part	150	70	10	N20W	10	3.1	4.6	0.5	10.2×10^{28}
	W part I	140	80	20	N50W	1	0	7.0	0.5	
	W part II	60	80	20	N30W	1	0	13.9	0.5	

L : fault length , w : fault width

δ : dip angle , φ : dip direction

z : depth of the upper rim of the fault plane

us : dislocation of strike slip component (right lateral)

ud :dislocation of dip slip component (reverse)

τ : duration time of the bottom movement

Mo : seismic moment (rigidity 5×10^{11} dyne·cm)

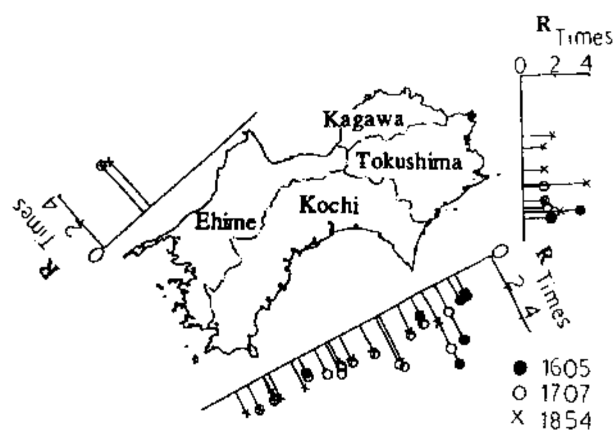

Figure 4. Comparison of historical tsunami heights

Basic Equations

The basic equations in the numerical simulation are the depth-averaged shallow water wave Eqs. (1)-(3) with a friction term and a convection term. It is supposed that the vertical displacement ξ of the sea bed is included.

$$\frac{\partial Q_x}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q_x^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{Q_xQ_y}{D}\right)+gD\frac{\partial \eta}{dx}+f_c\frac{Q_x\sqrt{Q_x^2+Q_y^2}}{D^2}=0 \qquad (1)$$

$$\frac{\partial Q_y}{\partial t}+\frac{\partial}{\partial y}\left(\frac{Q_y^2}{D}\right)+\frac{\partial}{\partial x}\left(\frac{Q_xQ_y}{D}\right)+gD\frac{\partial \eta}{dy}+f_c\frac{Q_x\sqrt{Q_x^2+Q_y^2}}{D^2}=0 \qquad (2)$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial Q_x}{\partial x}+\frac{\partial Q_y}{\partial y}+\frac{\partial \xi}{\partial t}=o \qquad (3)$$

Here x and y are the horizontal orthogonal coordinates fixed on the still water surface, Q_x and Q_y are the corresponding components of volume transport velocity integrated from the water surface to the bottom, g is acceleration due to gravity, f_c is the quadratic friction coefficient of the sea bottom, h is still water depth, η is the water surface elevation from still water level, ξ is the vertical displacement of the sea bed and $D=h+\eta\cdot\xi$. These equations are transformed to difference equations.

Computation Region and Boundary Conditions

Figure 5 shows the computation region and the fault model of the 1946 Nankaido earthquake. As shown in Figure 5, the computation region includes the Seto Inland sea and the Pacific Ocean around Shikoku island. The grid size of the computation region is 5km×5km and the time step in the numerical simulations is 5 sec.

As for the boundary conditions, it is assumed that tsunami waves reflect perfectly at the land boundaries and the volume transport velocity perpendicular to the face of solid boundary is zero. Moreover, the volume transport velocity at the offshore boundary is decided by using the relation of $Q_x^2+Q_y^2=gD\eta^2$.

Simulation of the Historical Tsunami

Numerical simulations were carried out for the 1707, the 1854 and the 1946 tsunamis by using the above-mentioned method. Figures 6.1-6.3 show the comparison of the calculated values with the observed values for these three historical tsunamis. The vertical axis shows the ratio R' of the observed value to the calculated value of a tsunami height.

These figures show the calculated values are generally smaller than the observed values. It is natural that the calculated results cannot accurately reproduce the tsunami heights at each location. Because the grid size used in our calculation is 5km in length, the computation region could not precisely represent the geographical features of the coast.

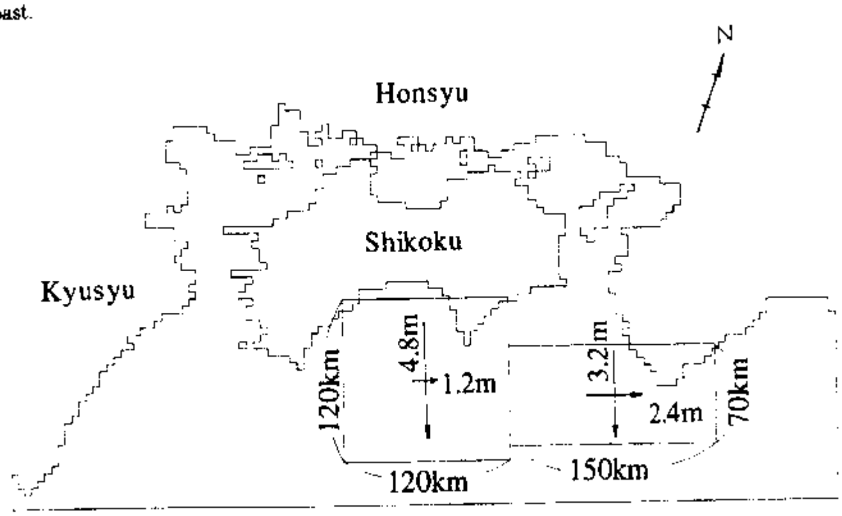

Figure 5. Computation region and the fault model of the 1946 Nankai earthquake

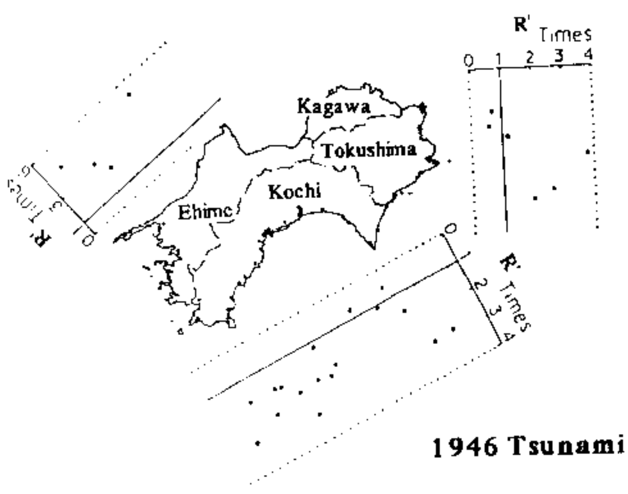

Figure 6.1. Comparison of calculated values with observed values

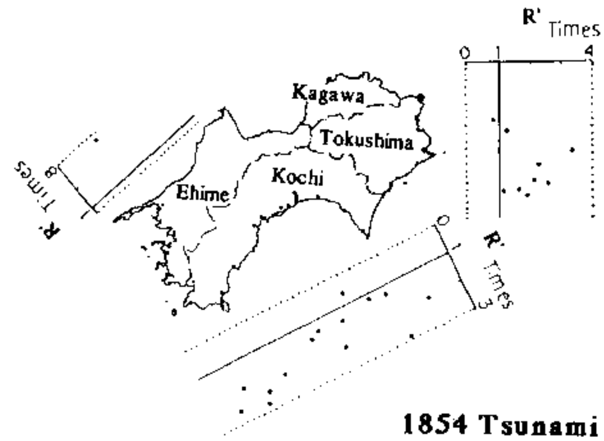

Figure 6.2. Comparison of calculated values with observed values

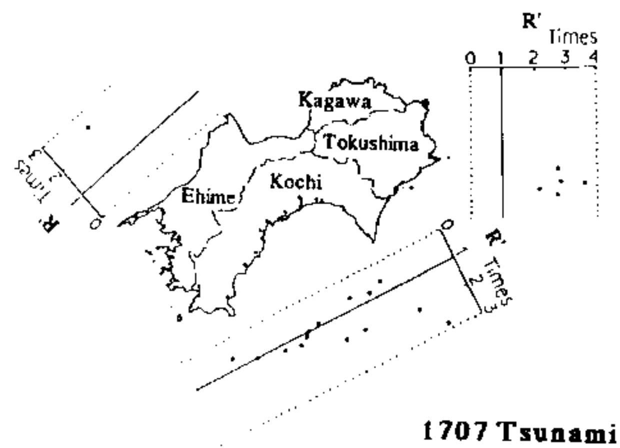

Figure 6.3. Comparison of calculated values with observed values

Figure 6.1 shows R' for the 1946 tsunami. The actual values of tsunami heights obtained by observation are 1-3 times as large as the calculated values along the Kochi coast. Along the Tokushima and Ehime coasts, the ratios maximize 4 times or more. However, the absolute values of the observed tsunami heights along the Ehime coast are not so high. For the 1854 tsunami in Figure 6.2, most values of R' are larger than 1.0 for the same reason mentioned above and the characteristics of R' between the 1946 and 1854 tsunamis show a similar tendency.

Figure 6.3 shows R' for the 1707 tsunami. For a long stretch along the Kochi coast, the values of R' are close to 1.0 and the tsunami heights by survey on the basis of old document are roughly equal to the numerically calculated ones. In the other regions (Tokushima, the eastern part of Kochi and Ehime), the observed values are larger than the calculated values. It is expected that in case of the calculation by 5km grid size, the calculated values are smaller than the observed ones, but most of the calculated values are almost equal to the observed ones for a long stretch along the Kochi coast. With considering these facts, it is necessary to re-estimate the fault parameters for the 1707 tsunami given in Table 1.

The Reproduction of the 1854 Tsunami Using the 1946 Tsunami Data

The characteristics of the 1854 tsunami are similar to those of the 1946 tsunam (See Table 1). So, we considered if the observed tsunami height at each bay end could b estimated by multiplying the calculated value of the 1854 tsunami by the value of R' fo the 1946 tsunami.

Figure 7 shows the ratio R" of this estimated value to the observed value for th 1854 tsunami. As shown in Figure 7, these values of R" are plotted around one. As result, the reproducibility of the 1854 tsunami heights was improved. Where we hav data for the 1946 tsunami, we can obtain the corresponding tsunami heights for the 185 tsunami by assuming that the source earthquakes were similar.

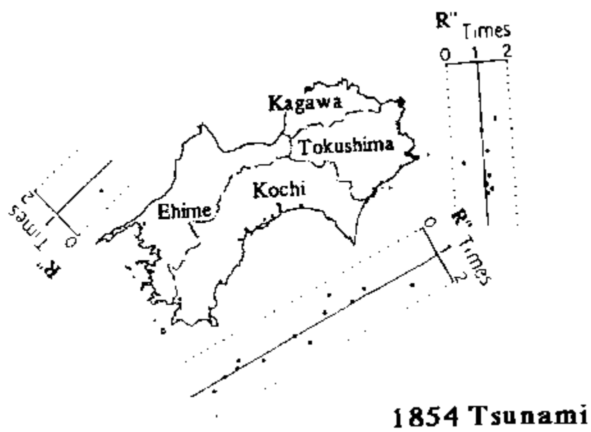

Figure 7. Reproduction of the 1854 tsunami

CONCLUSION

In this study, four big historical tsunamis were investigated in order to clarify tsunamis along the coast of Shikoku island in Japan.

First, data on the heights of these historical tsunamis occurring along the shikoku coast were re-examined. In addition, new data and the inundation heights of three of the historical tsunamis were compared with those of the 1946 tsunami.

Second, the inundation heights of these historical tsunamis were compared with the values calculated by numerical simulations. The following conclusions were obtained:

1) Generally, the values of tsunami heights of the three older tsunamis are 2-4 times as large as those of the 1946 tsunami.

2) It is necessary to re-estimate the fault parameters for the 1707 tsunami given in Table 1, because the observed values of tsunami heights are nearly equal to the calculated values for a long stretch of the Kochi coast in spite of the calculation by the 5km grid size.

3) The tsunami heights of the 1854 tsunami can be reproduced by using the observed data of the 1946 tsunami.

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