Natural Hazards **29:** 325–340, 2003.

Study on a Simplified Method of Tsunami Risk Assessment

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(Received: 31 October 2000; accepted: 15 February 2002)

Abstract. For the testing of the effect on the tsunami prevention facilities, a simplified method for tsunami risk assessment was suggested without wave run-up analysis. This method is proposed using calculated offshore tsunami waveform and field reconnaissance such as the seawall height, time necessary for residents' evacuation and tsunami warning insurance. Then, two normalized values are evaluated; one is the ratio of calculated maximum tsunami height to seawall height, the other is the ratio of time between tsunami over-topping and evacuation completion to total time required for evacuation. These two values are used to qualitatively estimate the safety of residents and the effect of tsunami prevention facilities, eliminating the necessity to compute complicated tsunami run-up onshore.

Key words: tsunami, earthquake, risk assessment, prevention facilities, evacuation.

1. Introduction

Many big earthquakes have occurred around the Nankai Trough, which runs from east to west of offshore Shikoku Island and Kii peninsula, Japan (here in Nankaido, Figure 1). The historical earthquakes have occurred at 100-to-150-year intervals, magnitudes have been near (or over) 8.0. Each time, residents living near the Nankaido suffer damage from tsunami disasters. The government has taken some counter measures against the next tsunami, for instance, breakwaters, seawalls, evacuation facilities and evacuation information.

For counter planning against tsunami disaster, the tsunami risks should be evaluated in detail. However, location of the next earthquake cannot be specified.

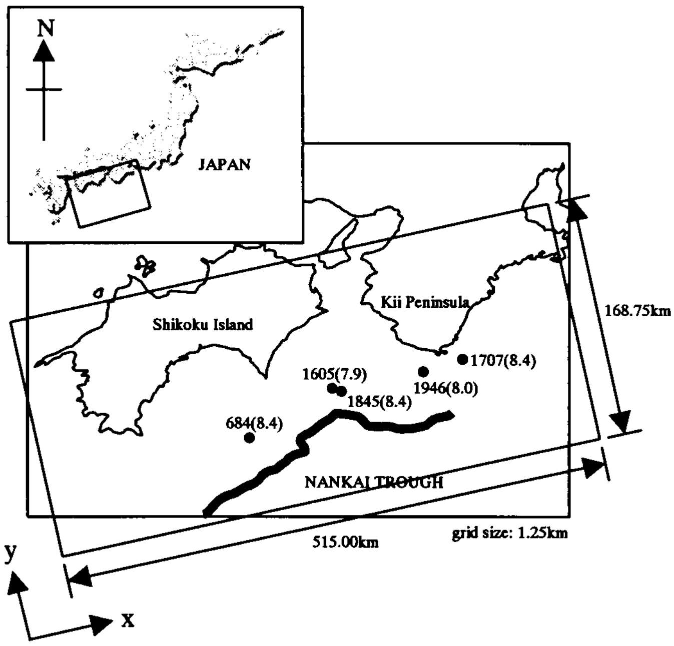

Figure 1. Calculation domain. Computation domain covers an area 515 × 168.75 km from Shikoku Island to Kii peninsula. At Nankaido, historical earthquakes have occurred around Nankai Trough.

Tsunami arrival time and tsunami height will change with the fault location. Supposing the same fault model of Ansei earthquake in 1854 is utilized in the theoretical calculation, the result values maybe change according to the different set-up of the model (Kawata and Koike, 1994). If the next earthquake occurs in a different place from historical earthquakes, more residents will suffer from the next tsunami because residents will act according to historical experiences. In this study, using the shifted fault models along the Nankai Trough, tsunami arrival time, tsunami height and "ratio of excess" were evaluated in detail.

The most effective counter measure differs from location to location. In areas where the tsunami will arrive very fast, the breakwaters and seawalls should be constructed first because residents will have no time for evacuation. If tsunami height is evaluated to be low, evacuation facilities should be maintained first. The government should grasp the effect of these measures, and should decide which ones to adopt. The safety of residents should be considered as the top issue. In particular, "ease of evacuation" becomes most important for reduction of damage to human beings. Recently, some research on evacuation has been reported. Kawata and Koike (1996), Inoue *et al.* (1996) and Shimada *et al.* (1999) assumed evacuation velocity and routes. Damage to human beings was estimated by using time series analysis based on the wave run-up calculations. However, these methods take a long time and much calculation data, and re-calculation is required when

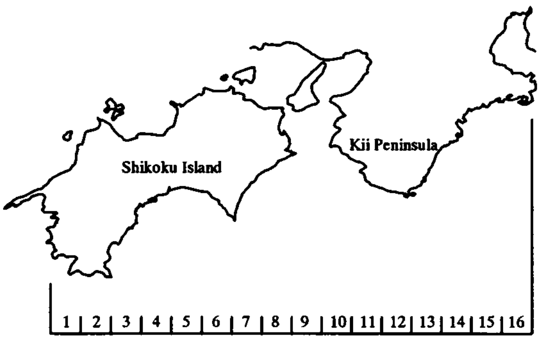

Figure 2. Discreet areas. For easiness of considerations, we divided computation domain into 16 area along coast of Nankaido.

other cases are supposed. In this study, a simplified method is proposed without calculations of wave run-up.

This report is composed of 4 Sections. In Section 2, using the shifted fault models along the Nankai Trough, tsunami arrival time, tsunami height and "ratio of excess" were evaluated. In Section 3, a simplified method is proposed, and tsunami risks are considered in detail. From calculated waveform and field reconnaissance, the overtopping risk and evacuation risk are defined. Section 4 contains conclusions.

2. Tsunami Risk Assessment Under the Shifted Fault Model

2.1. BASIC EQUATIONS AND CALCULATION DOMAIN

Figure 1 shows the computation domain of the present study, which covers an area 515.00 × 168.75 km. The coordinate system is also illustrated in Figure 1 where the symbol "●" indicates the historical earthquake epicenters at the Nankaido offshore. In history, at the Nankaido, all serious earthquakes occurred within this area.

For the case of computation, the computation domain is divided into 16 areas with equivalent distance along the coast of the Nankaido (about 35 km, as shown in Figure 2). The grid size for the numerical scheme is 1.25 km; the minimum water depth is 5.0 m; time step is chosen as 1 second for stability. In addition, offshore tsunami waves are calculated for one hour after the seabed displacement using two dimensional leap-frog method.

Basic numerical equations are Equations (1)–(3). The second and third terms at the left side of Equations (1) and (2) can be neglected when the water depth is over 50 m

$$\frac{\partial M}{\partial t} + gH\frac{\partial \zeta}{\partial x} + f\frac{MQ}{H^2} + \frac{1}{H}\left(M \cdot \frac{\partial M}{\partial x} + N \cdot \frac{\partial M}{\partial y}\right) = 0, \quad (1)$$

$$\frac{\partial N}{\partial t} + gH\frac{\partial \zeta}{\partial y} + f\frac{NQ}{H^2} + \frac{1}{H}\left(M \cdot \frac{\partial N}{\partial x} + N \cdot \frac{\partial N}{\partial y}\right) = 0, \quad (2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0, \tag{3}$$

where t denotes time; g is the gravity accelerator; ζ is water level lift from still water level; h is water depth; f is friction coefficient of ocean bottom; M and N represents the discharge flux in x and y direction, respectively; ξ is the vertical amount of seabed displacement, which can be estimated by Manshinha–Smylie theory (1971) by fault model. Here, ξ is simply considered as the wave surface change. In the above equations, H and Q can be yielded as

$$H = h + \zeta - \xi, \tag{4}$$

$$Q = \sqrt{M^2 + N^2}. \tag{5}$$

For boundary conditions, full reflection is assumed on the landward side, while non-reflection is used for other sides. Linear long propagating wave is assumed which fulfills Equation (6).

$$M^2 + N^2 = gH \cdot \zeta^2. \tag{6}$$

2.2. SHIFT RULES OF THE FAULT MODEL

How to determine the scale of tsunami is a problem for disaster prevention. Usually, the seawall design is based on storm surge, and the design of that for tsunami is based on the simulation result of the Chile tsunami in 1960 or Ansei tsunami in 1854 at the along of the Nankaido. However, it is difficult to predict which kind of tsunami can occur under different kinds of fault motion.

Figure 3 shows that three earthquakes were chosen as shift samples for fault models: the Showa earthquake model, Ansei earthquake model and Hoei earthquake model. Every fault models have fault parameters each other. The parameters used in numerical calculation were from No. 19 (Showa model), No. 20 (Ansei model) and No. 29 (Hoei model) of Aida Model (Aida, 1981).

As shown in Figure 1, the historical earthquakes always occur in the landward side of the Nankai Trough. Now, basic line 1 is assumed on the historical earthquake's epicenters (shown in Figure 3). Eight basic points are set on this line with equivalent interval of 64 km. Symbol "●" indicates the location of these points. It supposes that the relationship between the fault model center and the basic point are fixed. The fault model is shifted along the basic line 1 by these rules. In a similar way, another two basic lines, 25 km to the north and south of basic line 1, are set out. These are shown in the Figure 3. Thus, 3 models and 24 points (= 72 tsunamis) will be assumed along the Nankai Trough.

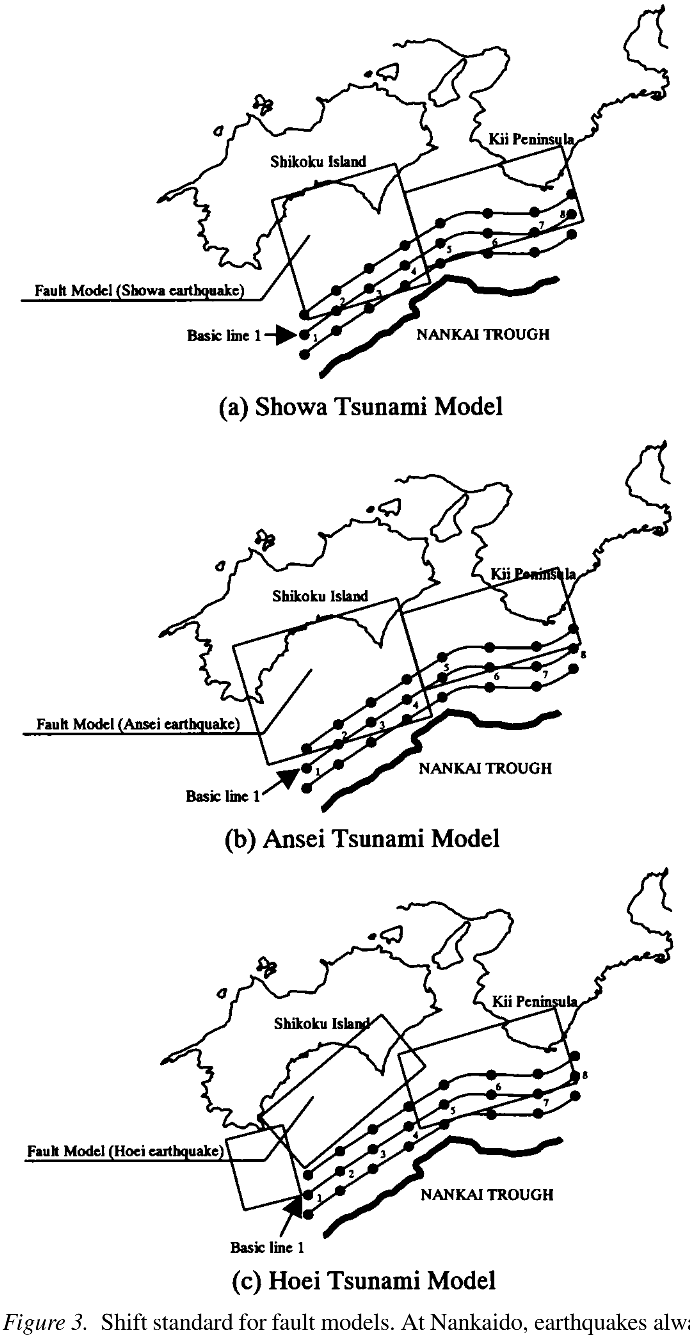

Figure 3. Shift standard for fault models. At Nankaido, earthquakes always occur on the landward side of Nankai Trough. Thus, we assume a base line 1 on these earthquake epicenters. Two other lines are set parallel to base line 1.

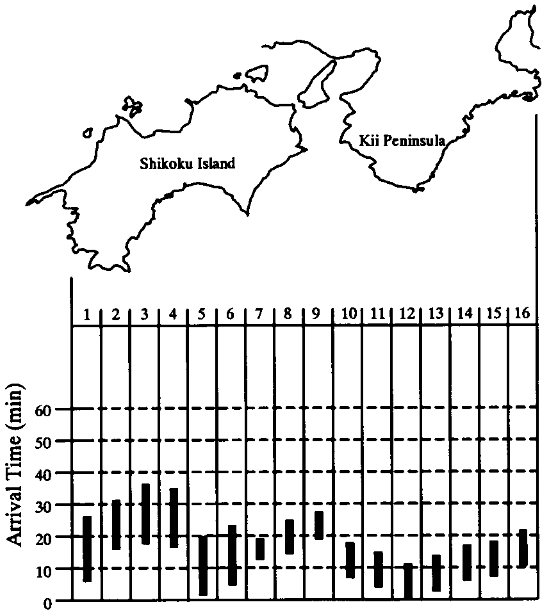

Figure 4. Spatial distribution of initial tsunami arrival time. All areas will be dangerous for tsunami because attacks within about 20 minutes after the seabed displacement.

2.3. ANALYSIS OF THE COMPUTATION RESULTS

2.3.1. *Arrival Time*

Figure 4 shows the spatial distribution of the initial tsunami arrival time (min) through the calculations of 72 tsunamis. According to Figure 4, from the view of arrival time, all areas will be attacked by tsunami within about 20 minutes after the seabed displacement. In particular, for the areas of Kii peninsula (areas 11, 12 and 13), tsunami attacks within about 10 minutes. Areas 1, 5 and 6, near the promontory of Shikoku Island, are similar. The results show that the tsunami attacks soon after the earthquake occurrence and could cause disaster for the residents living in the coastal areas.

2.3.2. *Ratio of Excess*

Figure 5 shows the “ratio of excess” for different areas. The “ratio of excess”, for example, can be defined as $P3=N_{A3}/N_T$. N_T is the total number of tsunami (=72). NA3 is the arrival number when tsunami wave height is over 3.0 m. In a similar way, $P5 = N_{A5}/N_T$ and $P7 = N_{A7}/N_T$ are defined. The tsunami risk can be evaluated by using these parameters. In Figure 5, the P3 values of shadowed areas 2, 7 and 10–12 indicate tsunami wave heights are almost over 3.0 m. Parameter P5 of areas 7 and 11 means the probability of tsunami wave height over 5.0 m is 0.7–0.9. Similarly, parameter P7 reaches 0.3. Therefore, area 7 is the most dangerous area considering tsunami wave height. For some of the other non-shadowed areas, the

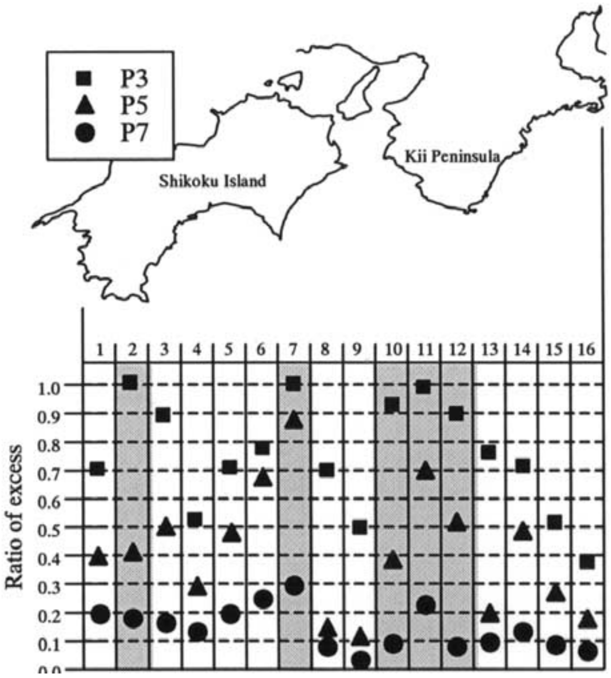

Figure 5. Spatial distribution of ratio of exceed. Shadowed areas – 2, 7, 10–12 are the most dangerous areas. Because, P3 is about 1.0 and P5, P7 is also high. P3 = 1.0 means that the tsunami height is over 3.0 m at every assumed cases.

risks can also remain high; for example, at area 6, P5 is over 0.6, and P7 is also high. Therefore, it is the general characteristic that the coast of Shikoku Island is more dangerous than Kii peninsula.

3. Suggestion of a Simplified Method of Tsunami Risk Assessment

3.1. OVERTOPPING RISK AND EVACUATION RISK

The index denoting "ease of evacuation" is chosen from the waveform calculated with the fault model and the field reconnaissance. Two "times" are given by using these indexes. One is tsunami transportation time from the seabed displacement to wave overtopping, the other is evacuation time of resident (varied with evacuation facilities and effectiveness of the alarm system) after the seabed displacement. Using the method applied in the research, we will be able to evaluate the efficiency of disaster prevention facilities. Here, there is no need to consider wave run-up, because the risk evaluation is fully influenced by the waveform between seabed displacement and wave overtopping. More fine grids will be needed in order to accurately calculate the waveform. However, this method is simple and evaluates the effect of the facilities for disaster prevention. In this case study, the largest

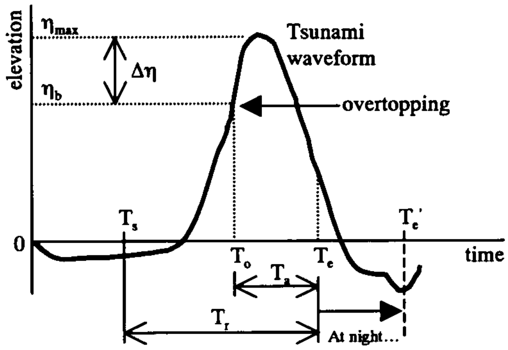

Figure 6. Example of calculation tsunami waveform of Usa town. This is a waveform calculated with infinite seawall height. Therefore, it may be different from real waveform. From $\eta_{\max}$, however, we can grasp the potential of tsunami height.

tsunami is selected for consideration. The largest tsunami is simulated by the fault model, which is shifted along the Nankai Trough.

Figure 6 indicates an example of calculated tsunami waveform at Usa Town, Shikoku Island when Hoei earthquake was calculated at basic point 7 (shown in Figure 3(c)) by fault model. The following are the notations of parameters. First, "t" denotes time, $t = 0$ indicates the start of seabed displacement. After "T_s" minutes, the residents will start to escape when they receive the warning issued. If the necessary time for evacuation is assumed "T_r", the total time for evacuation from seabed displacement will be denoted as $T_e = T_s + T_r$. Perhaps, if the tsunami attacks in the night, much more time will be needed, and point T_e will shift to T_e'. While, "T_o" is the time of the water level rises to the present seawall height (η_b). Here, the value of "Ta" is defined as $T_a = T_e - T_o$. We can judge whether the residents will be able to evacuate safely or not. For example, if $T_a/T_r < 0.0$, residents will complete the evacuation before tsunami overtopping. While, "$\eta_{\max}$" is maximum wave height calculated by using infinite seawall height. Therefore, $\eta_{\max}$ sometimes exceeds η_b. We can judge whether the tsunami will overtop the present seawall or not. For instance, if $\eta_{\max}/\eta_b > 1.0$, the tsunami will run-up into the town. In order to easily compare risk in different areas, these parameters are renamed as $R_o = \eta_{\max}/\eta_b$ (here, overtopping risk) and $R_e = T_a/T_r$ (here, evacuation risk). When R_o and R_e are plotted on the same diagram, it becomes easy to evaluate the risks of tsunami wave height and residents evacuation.

Figure 7 indicates the overtopping risk and evacuation risk of Usa Town with the waveform shown in Figure 6. It is assumed that there is much risk when R_o is over 1.0 and R_e is over 0.5, respectively. The shadowed area shown in Figure 7 is not safe. The facilities with smaller $\Delta\eta$ ($= \eta_{\max} - \eta_b$) and T_a are in favor. $\Delta\eta$ will be reduced with the increase of η_b or constructing the tsunami breakwater to reduce $\eta_{\max}$. There are three methods to reduce T_a: the first is evacuation training or rapid tsunami alarm which leads to less evacuation time T_s; the second is to set guided indicator board and light which are effective in evacuation; the last one is

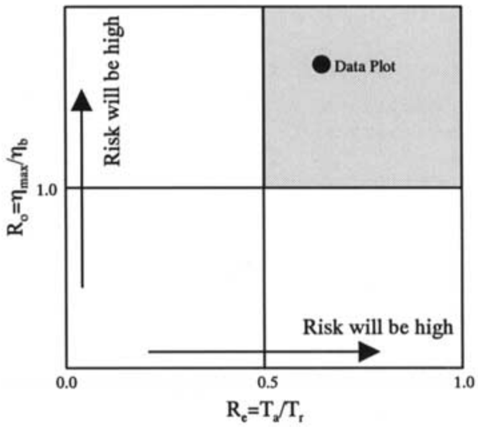

Figure 7. Example of overtopping risk and evacuation risk.

increasing seawall height η_b to delay overtopping time T_o. In a word, improvement of η_b, T_s, T_r will reduce the loss of human lives.

3.2. DETERMINATION OF PARAMETERS η_b, t_s, t_r

In order to evaluate risk with overtopping risk and evacuation risk, the η_b, T_s, T_r should be defined. Assuming the tsunamis attacking in the night, the parameters are defined as follows:

(a) In order to obtain waveform for risk evaluation, Houei model, the largest tsunami model along Nankaido is shifted to the most dangerous basic point.
(b) η_b is the height of present seawall.
(c) T_s is chosen as 2 minutes (resident with high consciousness can escape immediately when the earthquake occurs) or 10 minutes (in the area with incomplete alarm system, 5 minutes used for sending alarm, another 5 minutes used for the aged starting to escape.)
(d) T_r: the longest distance for evacuation/escaping velocity of the aged (40 m/min in the daytime; 20 m/min in the night).

Referring to other constructed breakwaters or breakwaters under construction, the wave height is considered as 1/3∼1/2 compared with infinite seawall version, because there is no calculation to show the effect of breakwater in detail.

3.3. DISCUSSION

Area 3 and 7 are picked up as a representative high-risk area. Risk evaluation is carried out with arrival time, maximum wave height, ratio of excess (P5), and newly defined overtopping risk and evacuation risk.

3.3.1. *Yaiga ∼ Usa (Area 3)*

Figure 8 shows the location of Area 3 and the estimated risks.

(a) *Arrival time*
Calculations based on basic point 3∼5 (shown in Figure 3) will supply the fastest arrival tsunami in this area. The arrival time in Susaki Bay and Usa Bay is over 20 min, and other areas are about 20 min. For historical tsunami arrival times were about 20 min. If this is demonstrated by the facts, risk will be similar to historical tsunamis. As the following description shows overtopping risk and evacuation risk are also high. Thus, this area should be paid more attention. In addition, since Susaki has a large population, evacuation may not be smooth. The consciousness of disaster prevention will affect the extent of damage.

(b) *Maximum wave height and ratio of excess (P5)*
When the fault model shifts from basic point 3 to point 6, maximum wave height occurs. The simulation results are 2.0m higher than the historical records. Particularly, the calculated wave height is over 10 m in Susaki and Usa which suffered large tsunamis before. From value of P5, the ratio of excess is 0.7 for the inner part of Susaki Bay. Therefore, counter measures against tsunami should be fully discussed.

(c) *Overtopping risk and evacuation risk*
Figure 9 shows the overtopping risk and evacuation risk in Area 3. Both of them point to a high-risk zone in every town. The main reason is the low present seawall height. And there are no evacuation facilities. The typical example is Susaki. The overtopping risk and evacuation risk at Susaki are shown in Figure 10 at plot-A.

Assuming that the present seawalls are only utilized, plot-A indicates the highest risk. Considering the intensive population, such high risk will produce large damage. However, supposing the effect of constructing the tsunami breakwaters, overtopping risk and evacuation risk will shift to plot-B shown in Figure 10. Without consideration of the damage of property, loss of life can be reduced through assignment of evacuation area, i.e., residents can escape to new evacuation spaces within 20 min instead of 30 min.

3.3.2. *Kannoura ∼ Yuki (Area-7)*

Figure 11 shows the location of Area 7 and the estimated risks.

(a) *Arrival time*
In history, this area frequently suffers tsunamis; immediately, the loss of residents is very large. For instance, the Showa earthquake and tsunami in 1946 caused 66 deaths in Asakawa. While, in a coastal community of Shikoku Island, the average number of deaths is about 10. The main reason lies in the fast arrival time and high

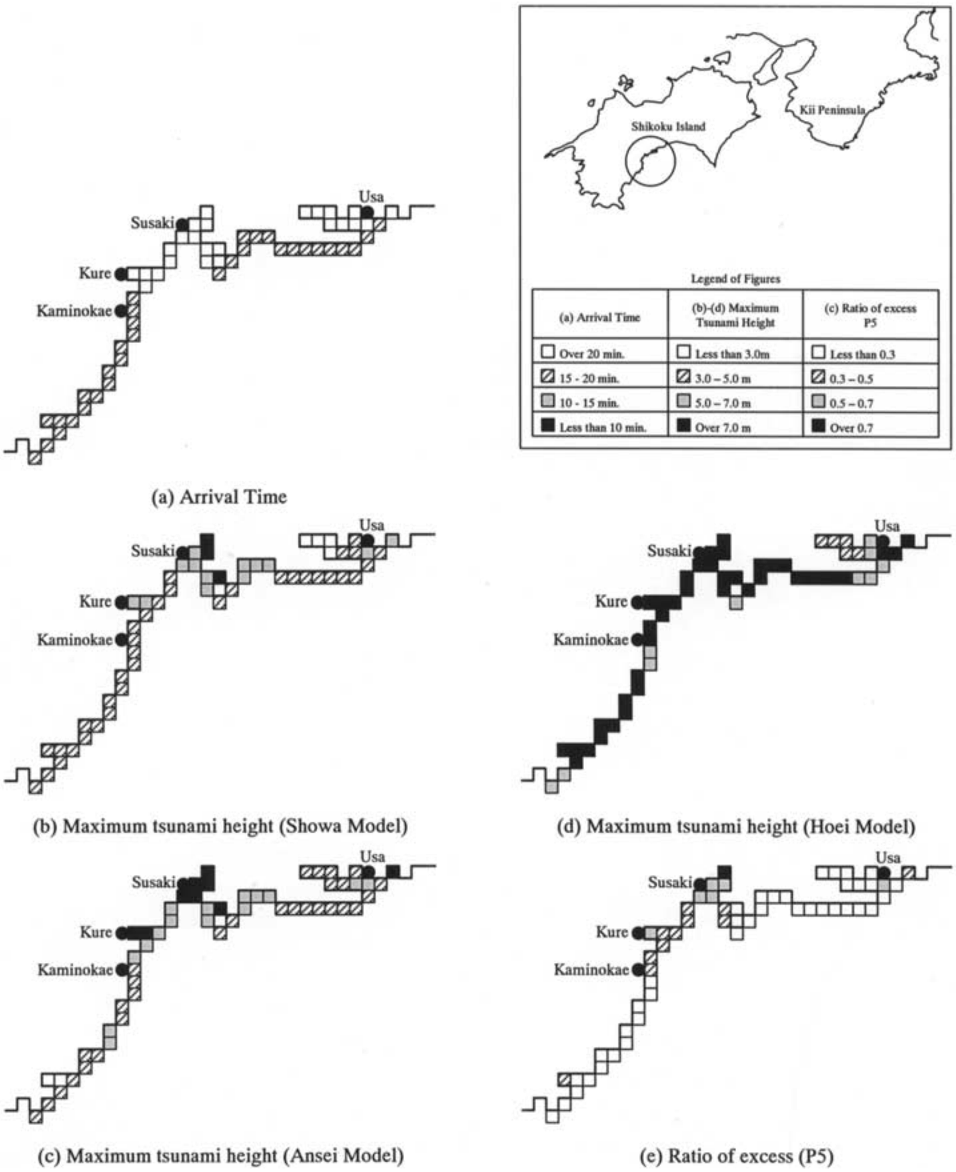

Figure 8. Spatial distribution of tsunami risks (Area-3). At the inner part of Susaki Bay and Usa Bay, tsunami arrival time is over 20 min. However, tsunami height is very high compared with the other towns. Especially at inner part of Susaki Bay, tsunami height will be over 7.0 m at all cases.

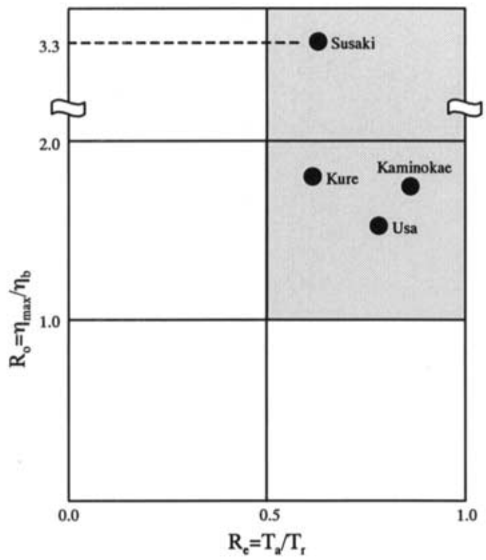

Figure 9. Overtopping risk and evacuation risk at Area-3. In this area-3, every town is dangerous. At Susaki, the overtopping risk (R_O) indicates 3.3. It means that the maximum wave height is very high, and we can not prevent tsunami disaster without 3.3 times seawall height.

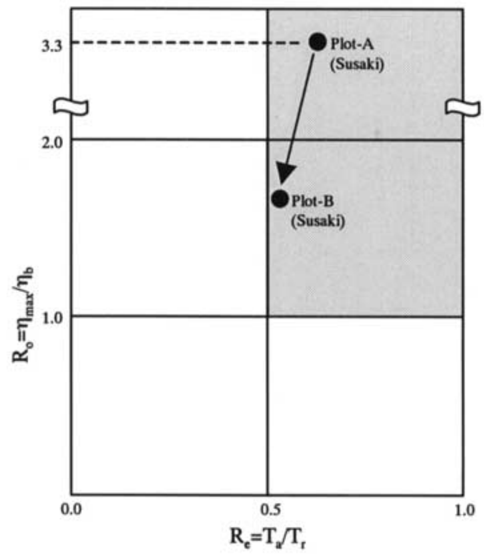

Figure 10. Effect of constructing the tsunami breakwater at Susaki. At Susaki, when we don't consider the tsunami breakwater, the overtopping risk and evacuation can be plotted at A. If the tsuname breakwater is complete, Plot-A will move to Plot-B. Consideration of tsunami breakwater tsunami height becomes low and start time of overtopping also slows.

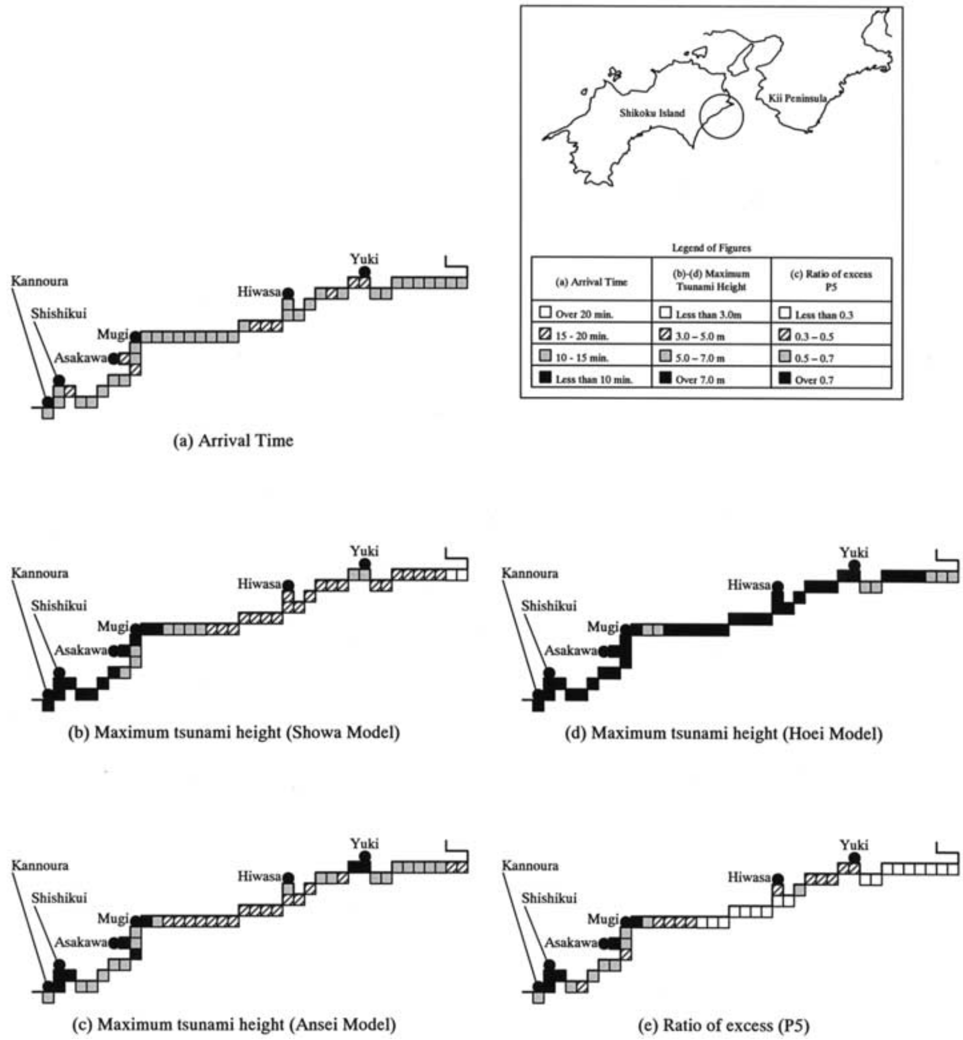

Figure 11. Spatial distribution of tsunami risks (Area-7). Compared with area-3, the arrival time is shorter. But, the tsunami height is also high. At Shishikui, Asakawa, Mugi and Yuki, where damaging tsunami disasters have occurred in the past, the ratio of excess is over 0.7. It denotes that the tsunami height will be over 5.0 m at probability of 70%.

tsunami wave. From Figure 11(a), all the arrival times are within 15 min. Historical records prove this result. It is predicted the next tsunami will arrive within 15 min after the seabed displacement.

(b) *Maximum wave height and ratio of excess (P5)*

From Figure 5, the value of P3 is 1.0 and P5 is about 0.9 at this area 7. It means that the wave heights are almost over 5 m no matter where the fault model is shifted. The simulation wave height of Kannoura ∼ Yuki is more than 3.0 m. And, using

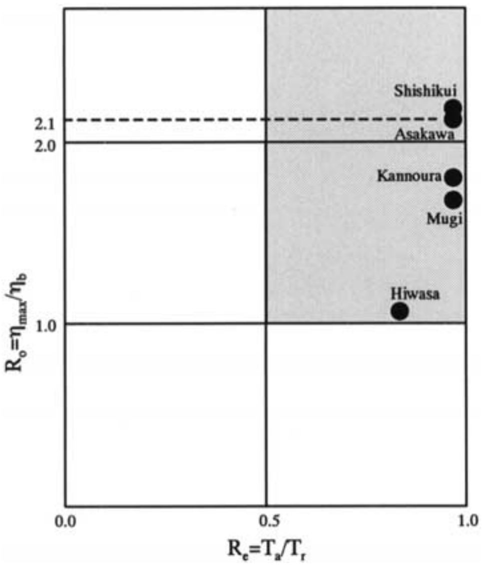

Figure 12. Overtopping risk and evacuation risk at Area-7. At these towns, we can see that they cannot avoid loss of residents in the next tsunami without considering the smooth evacuation.

Hoei model, the tsunami heights are over 7.0 m at almost all towns. This result can be obtained from ratio of excess (P5) that is over 0.7.

(c) Overtopping risk and evacuation risk

Figure 12 shows the overtopping risk and evacuation risk of this area 7. In this area, the evacuation risk indicates nearly 1.0. It is most important to consider the smooth evacuation. Even for this area, the loss of residents could be reduced if a secure system were set up. Asakawa is a good example. The consciousness against tsunamis in this town is probably the best in Shikoku Island. The evacuation spaces, guided boards and guided lights are set here and there. In order to surmount the short height of the present seawall, tsunami breakwaters have been constructed. Figure 13 shows the overtopping risk and evacuation risk of Asakawa. Plot-A indicates the risk without disaster prevention facilities. While, Plot-B is with it. By the evacuation facilities, the evacuation risk is reduced and damage and loss of residents. If the new breakwaters are completed, the wave height can be assumed to reduce to 1/2 compared with non-breakwater version (plot-B). It is predicted that the risk can decrease to the level where the present seawall can prevent the tsunamis (plot-C). In order to make full use of evacuation facilities, the more important thing is to do evacuation training at least one time each year and improve the consciousness of residents. By this way, residents can get to know what kind of routine and place will be safe for evacuation.

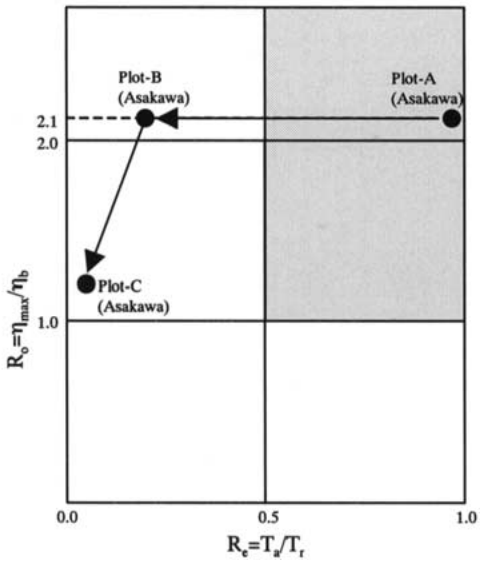

Figure 13. Effect of tsunami prevention structures at Asakawa. Plot-A indicates the overtopping risk and evacuation risk without disaster prevention facilities. While Plot-B is with it and, at Plot-C, the tsunami breakwater is complete.

4. Conclusions

Risk evaluation was performed on the grid with 1.25 km-mesh. Using the shifted fault models, the tsunami arrival times, tsunami heights and the new index denoting "ratio of excess" were estimated in detail. Tsunami arrival time and tsunami height changes by the fault location. If the next earthquake occurs at a different location from historical earthquakes, more residents will suffer from next tsunami. In areas without tsunami disasters before, it is possible to consider the location and scale of tsunamis as well as measures against disaster.

Overtopping risk and evacuation risk were defined by calculated waveform and field reconnaissance, such as seawall height, necessary time of residents' evacuation and announced time of tsunami warning. The effects of present tsunami prevention facilities were estimated quantitatively. It is also a premise for the reasonable set-up of tsunami prevention facilities. The limits of the overtopping risk and evacuation risk were set. The counter measures against tsunami should be enforced following these limits. For the area where tsunami height is high and arrival time is fast, construction of the tsunami breakwater and smoothness of evacuation will reduce the loss of residents' lives.

Acknowledgement

A part of the present investigation was accomplished with the support of the Science Research Fund of the Ministry of Education (Grant-in-Aid for Science Research (C)(10680446)), for which the authors express their appreciation.

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