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SOME SIMULATIONS FOR ASSESSMENT OF EARTHQUAKE HAZARDS IN THE JAPANESE ISLANDS BY USE OF THE ACTIVE FAULT CATALOGUE AND HISTORICAL RECORDS

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SUMMARY

The present paper evaluates the hazards of earthquake occurrences from active fault systems in Japan, by statistical simulations. The following points become clear from the study of the present paper

1) The frequency of earthquake occurrence in historical record is in fair agreement with that of the number of large seismogenic active fault systems discovered in Japan and with their activities. Here, the activities are estimated by the distribution of simulated mean recurrence intervals and the elapsed times since the most recent earthquake events of the active fault systems.

2) When the probabilities that earthquakes will occur from active fault systems within the next 30 years (30-year probabilities) are simulated due to the variation of recurrence intervals (i.e. with the coefficient of variation of 0.298 in logarithmic normal distributions), the following can be detected:

(1) 30-year probabilities of one-third of active fault systems would be smaller than 10^{-8}
(2) 30-year probabilities of half of active fault systems would be larger than 10^{-3}
(3) 30-year probabilities of one-third of active fault systems would be larger than 10^{-2}
(4) 30-year probabilities of about 10% of active fault systems would be larger than 0.03
(5) 30-year probabilities of very few active fault systems would be larger than 0.10

Note that these are the results of simulations based on the assumption that each active fault system is acting independently.
Great historical intraplate earthquakes from the active faults in Japan occurred after long elapsed times since previous earthquake events, and when the 30-year probabilities were large. All these earthquakes occurred from the active faults studied by trenching investigations, and their 30-year probabilities are estimated by a subcommittee for Long-term Evaluation of Earthquake Research Committee of the Headquarters for Earthquake Research Promotion. The 30-year probabilities of these active faults can be ranked very highly when the earthquakes occurred.

INTRODUCTION

The aim of the present paper is to prepare a hazard assessment of large intraplate earthquakes caused by seismogenic active fault systems distributed in the Japanese archipelago. The hazards are assessed and shown as frequencies of, and probabilities of, earthquake occurrences for each Japan Meteorological Agency local scale magnitude (hereinafter M_{JMA}). The aim is accomplished by utilising knowledge described in the following figures.

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Firstly, Figure 1 shows the distribution of major active fault systems in Japan. This is of geomorphologically recognised active fault systems from where earthquakes of $M_{JMA} \geq 6.5$ will occur (Kumamoto 1998). Here each M_{JMA} is estimated by an empirical relation between fault lengths L and M_{JMA} as follows (Matsuda 1975):

$$\log L = 0.6\, M_{JMA} - 2.9 \quad (1).$$

As shown in the figure, active fault systems are distributed all over the Japanese archipelago, especially in the central region. While intraplate earthquakes with a depth of 20 km or shallower have periodically caused many great disasters in Japan, most were produced by the active fault systems shown in Figure 1. Although other intraplate earthquakes are being generated more frequently all over the Japanese archipelago, their M_{JMA} are rather small. This paper focuses only on the large active fault systems in the figure, where large earthquakes earthquake of each fault system in Figure 1 in order to achieve risk assessments for future great earthquake disasters.

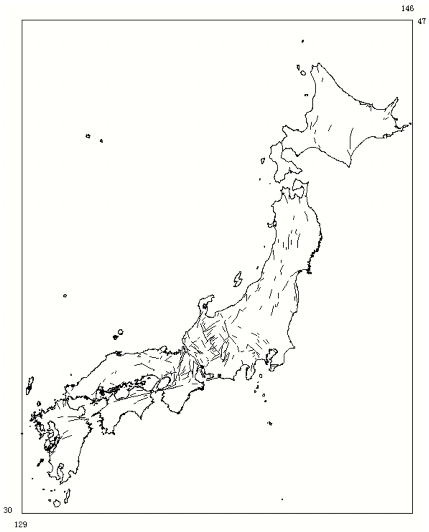


Figure 1 Distribution of Active Fault Systems in the Japanese Islands

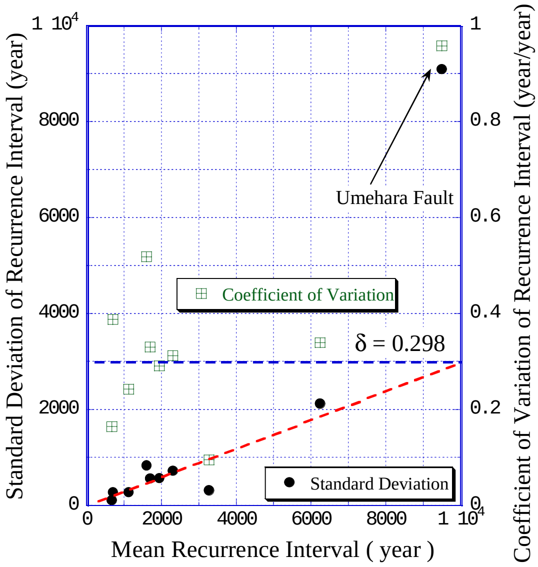


Figure 2 Standard Deviation and Coefficient of Variation vs. Mean Recurrence Interval

Secondly, Figure 2 shows the relation between mean recurrence intervals and their standard deviations. Each mean and standard deviation of the recurrence intervals relates to an active fault system. As shown in the figure, the standard deviations are approximately proportional to the means, and the coefficient of variation (proportionality constant) is 0.298. From a statistical point of view, this coefficient of variation of 0.298 suggests the periodicity of earthquake occurrences at each active fault system. A subcommittee for Long-term Evaluation of Earthquake Research Committee of the Headquarters for Earthquake Research Promotion also investigated the activity of some active faults in Japan. In their results, the subcommittee found that probability models of periodical earthquake occurrences (e.g. logarithmic-normal distributions) are much more suitable for describing the activity of each active fault system than non-periodical ones (e.g. exponential distributions). The subcommittee also reported that the coefficient of variation would be between 0.2 and 0.3, which means that approximating the coefficient of variation of 0.298 is rather discreet assumption in predicting earthquake occurrences. Thus, a logarithmic normal distribution is used in the present paper simply as a rough approximation for the probability model of recurrence intervals ΔT (year) of each active fault system, shown as follows:

$$f_{\Delta T}(\Delta T) = \frac{1}{\sqrt{2\pi}\sigma_{\Delta T}\Delta T}\exp\left\{-\frac{1}{2}\left(\frac{\ln\Delta T - \ln\mu'_{\Delta T}}{\sigma_{\Delta T}}\right)^2\right\} \quad \text{(2), where the mean recurrence interval}$$

$$\mu_{\Delta T} = \mu'_{\Delta T}\exp\left(\frac{1}{2}\sigma^2_{\Delta T}\right)(\mu'_{\Delta T} = \text{geometric mean}) \quad \text{(3), and } \delta_{\Delta T} = \sqrt{\exp\sigma^2_{\Delta T} - 1} = 0.298 \quad \text{(4).}$$

Here, the mean recurrence interval $\mu_{\Delta T}$ (year) is inherent to each active fault system.

SIMULATIONS OF RECURRENCE INTERVALS

Method of Performing Simulations

According to trenching studies on active faults in Japan, recurrence intervals of intraplate earthquakes are hundreds or thousands of years, or even longer. These are much longer than those of interplate-type faults, such as the Alpine Fault in New Zealand or the San Andreas Fault in California. Moreover, not all recurrence intervals have been clarified yet in Japan since the number of trenching studies is small compared with that of active fault systems. Therefore, the authors here adapt a Monte Carlo simulation of geomorphologically-derived slip rates *D* (m/1000 year) of active fault systems in Figure 1 to predict the distribution of mean recurrence intervals. This is because the mean recurrence interval $\mu_{\Delta T}$ can be calculated with the earthquake moment M_o (dyne·cm) and with the earthquake moment rate M_o (dyne·cm/year) as follows (Wesnousky et al. 1984):

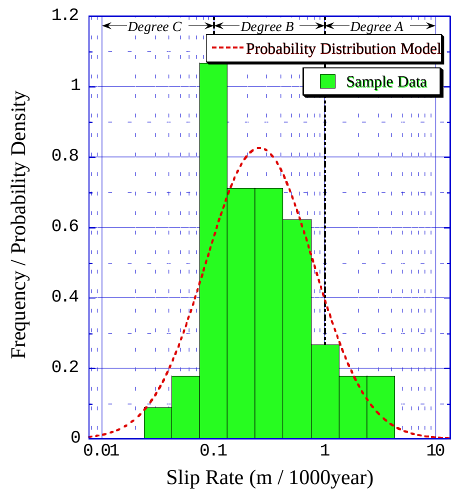


Figure 3 Frequency of Slip Rates *D* of Sample Data and Its Probability Distribution Model

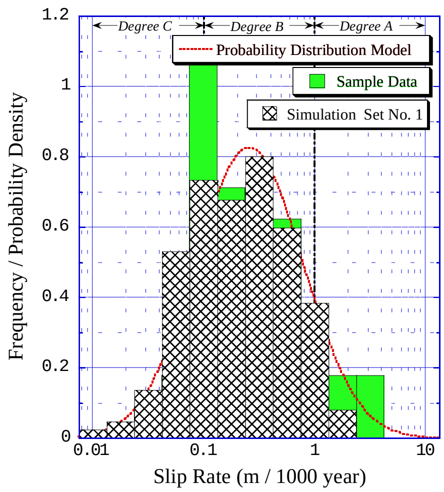


Figure 4 (a) Frequency of Simulated Slip Rates *D* (Set No. 1)

$$\mu_{\Delta T} = M_O / \dot{M}_O \quad (5), \quad \text{where} \quad \log M_O = 1.94 \log L + 23.5 \quad (6), \quad \text{and} \quad \dot{M}_O = \nu \cdot \dot{D} \cdot L \cdot W \quad (7).$$

Here ν is the rigidity of the Earth's crust (=3.3×10^{11} dyne/cm^2), and *W* (km) is the depth of the active fault system (*W*=*L* for *L*<20km, *W*=20km for others). Specifically, $\mu_{\Delta T}$ can be calculated based on eqs.(5)~(7) when *D* is simulated, because lengths *L* of each active fault system have been listed (Kumamoto 1998).

Simulations of Slip Rates D

Slip rates of the large active fault systems shown in Figure 1 are simulated based on the frequency distributions of their sample data. Any slip rates are, however, not simulated when the mean recurrence intervals of the active fault systems are estimated using the results of trenching investigations. In general, only order of magnitude of slip rate is evaluated for each active fault system, and expressed in three degrees. Here, the three degrees mean that a slip rate is of degree *A* when it is between 1~10(m/1000 year), of degree *B* when between 0.1~1(m/1000 year), and of degree *C* when between 0.01~0.1(m/1000 year). (Note the descriptions on the top and the horizontal axes of Figure 3). Namely, there is a difference of order of magnitude within one degree. In some large active faults, however, the slip rates are investigated in more detail. Figure 3 shows the frequency distribution of such slip rates. This is for all slip rates whose fault lengths are shown as more than 10km on the maps of "Active Faults in Japan" (The Research Group For Active Faults of Japan 1991). Although slip rates of degree *C* are found more in smaller active faults on the maps, eq.(1) does not predict that such great earthquake disasters would occur at those locations, and they are thus ignored. As is clear from Figure 3, the frequency of these sample slip rates can be approximated by a normal distribution. Therefore, slip rates *D* of the other active fault systems are simulated as a rough approximation by random values generated from the normal distribution in Figure 3.

Figure 4 shows the frequency distribution of simulated slip rates D. While the simulations are performed ten times, all of them result in a similar frequency distribution. Therefore, only the first set of simulations is usually shown in the present paper. Figure 4 also shows the frequency distribution of the sample slip rates data and the probability distribution in Figure 3. As is clear from the figure, the frequency distribution of simulated slip rates is in fair agreement with that of sample data, due to the large number of simulated slip rates.

Simulations of Mean Recurrence Intervals $\mu_{\Delta T}$

Figure 5 shows the frequency distribution of mean recurrence intervals $\mu_{\Delta T}$, calculated from the simulated slip rates D based on eqs.(5)~(7). As is clear from the figure, mean recurrence intervals are mostly distributed between thousands and tens of thousands of years. This distribution is in accord with findings of geological researchers at trenching in-situ.

Frequency of Earthquake Occurrences Obtained from the Simulated Mean Recurrence Interval, and Its Comparison with That of Historical Earthquakes

Here, the average earthquake occurrence frequencies are calculated using the simulated mean recurrence intervals. Firstly, the frequency of earthquake occurrence f_{mi} (1/year) of each active fault system i is calculated as the inverse value of its mean recurrence interval $\mu_{\Delta Ti}$ as follows:

$$f_{m_i} = 1/\mu_{\Delta T_i} \quad (8).$$

Secondly, the cumulative frequency of earthquake occurrences for each magnitude M_{JMA} is calculated as follows:

1) M_{JMA}, characteristic of each active fault system, is estimated from its fault length L based on eq.(1).
2) the average cumulative frequency for each M_{JMAj} is calculated by summing the f_{mi} of the active fault system of $M_{JMA} \geq M_{JMAj}$

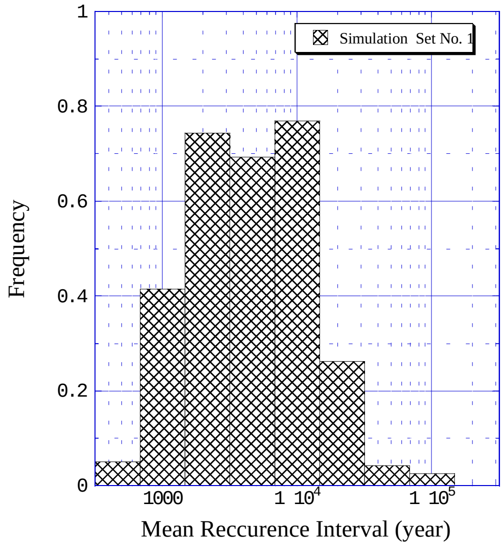
Figure 6 shows the cumulative frequency of earthquake occurrences for each M_{JMAj} using the results of all ten sets of simulations. Figure 6 also shows the cumulative number of active fault systems for each M_{JMAj} (indicated on the right axis), and cumulative frequencies of historical earthquake occurrences in the Japanese archipelago for each $M_{JMA\,j}$. This is described only by historical earthquake records of the last 400 years in Japan (Usami 1998). As shown in the figure, only one historical earthquake event of $M_{JMA} \geq 7.7$ from an active fault system is recorded in the last 400 years, while events of $M_{JMA} \geq 7.0$ are recorded every 13~14 years, and events of $M_{JMA} \geq 6.5$, once every 6~7 years. Note that the accuracy of estimating each M_{JMA} based on eq.(1) is rough from a fault segmentation and grouping viewpoint. For example, the length L of the Neodani Fault System is less than 80 km, and thus the estimated M_{JMA} of this active fault system based on eq.(1) is less than 8.0. However, the Great Nobi Earthquake of M_{JMA}=8.0 occurred from this active fault system in 1891. Therefore, attention should be paid to the fact that eq.(1) contains some error, and earthquakes greater or smaller than that estimated using eq.(1) might occur.

As is clear from Figure 6, however, the cumulative frequencies given by the simulations are in accord with those of historical record. It is also clear that the variation between simulation sets is small, except in a small range where magnitudes are large (the number of active fault systems is small).

SIMULATIONS OF ELAPSED TIMES FROM THE MOST RECENT EARTHQUAKE EVENTS

Method of Performing Simulations

The elapsed times Δt (year) are simulated in this chapter based on the mean recurrence interval $\mu_{\Delta T}$ simulated in chapter 2. Here, a probability model for the simulations is introduced for the case where no information about Δt is given. The "no information" means here that the most recent earthquake event of each active fault system might have occurred yesterday or an extremely long time ago. It is assumed, however, that the mean recurrence interval $\mu_{\Delta T}$ of each active fault system is given.



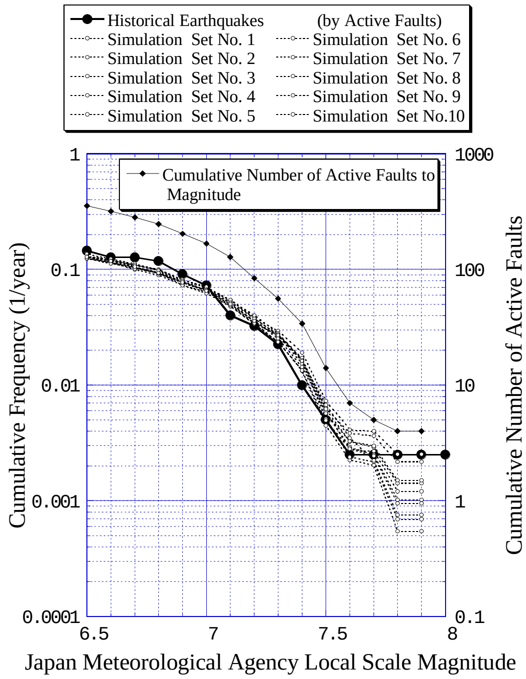


Figure 5 (a) Frequency of Simulated Mean Recurrence Intervals $\mu_{\Delta T}$ (Set No. 1)

Figure 6 Simulated and Historical Cumulative Frequency of Earthquake Events vs. M_{JMA}

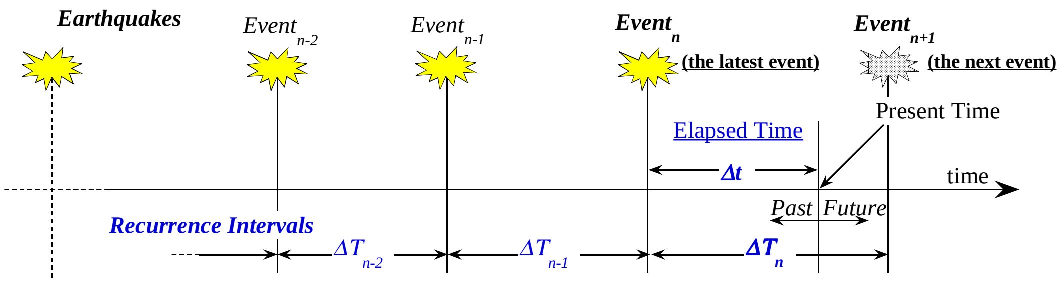


Figure 7 Modelling of Probability Distribution of Elapsed Time ΔT

Figure 7 shows a model of a time series of earthquake occurrences from an active fault system. As shown in the figure, several earthquakes have occurred from this active fault system, and each recurrence interval is indicated by ΔT_i. Here, the most recent earthquake event from this active fault system is indicated as $Event_n$ and the next $Event_n$ following is $Event_{n+1}$. Namely, $Event_{n+1}$ is the first earthquake event of those that will occur in the future. Note that ΔT_n (year) is the recurrence interval between $Event_n$ and $Event_{n+1}$. Clearly, ΔT_n is longer than the elapsed time Δt (year) since $Event_n$ to the present time. Then, as "no information" about Δt is assumed here, the probability distribution model of Δt can be expressed as follows:

$$f_{\Delta t}(\Delta t) = 1/\Delta T_n \quad (9), \quad \text{where} \quad \Delta T_n \geq \Delta t \quad (10).$$

On the other hand, the probability distribution of ΔT_n (year) is given as eq.(2). Therefore, eq.(9) is re-expressed with eqs.(2) and (10) as follows:

$$f_{\Delta t}(\Delta t) = \int \frac{1}{\Delta T_n} \cdot f_{\Delta T}(\Delta T_n)\, d\Delta T_n = \frac{1}{\mu'_{\Delta T}} \exp\left(\frac{\sigma_{\Delta T}{}^2}{2}\right) \int_{-\infty}^{\frac{\ln(\mu'_{\Delta T}/\Delta t)}{\sigma_{\Delta T}} - \sigma_{\Delta T}} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} s^2\right) ds \quad (11).$$

Figure 8 shows a probability density distribution (indicated on the left axis) and its cumulative probability density distribution (indicated on the right axis) of eq.(11) for the case of a mean recurrence interval $\mu_{\Delta T}$ of 1000(years). As shown in the figure, the probability density is large for $\Delta t \leq 700$(year), and small for $\Delta t \geq 1200$(year) in this case.

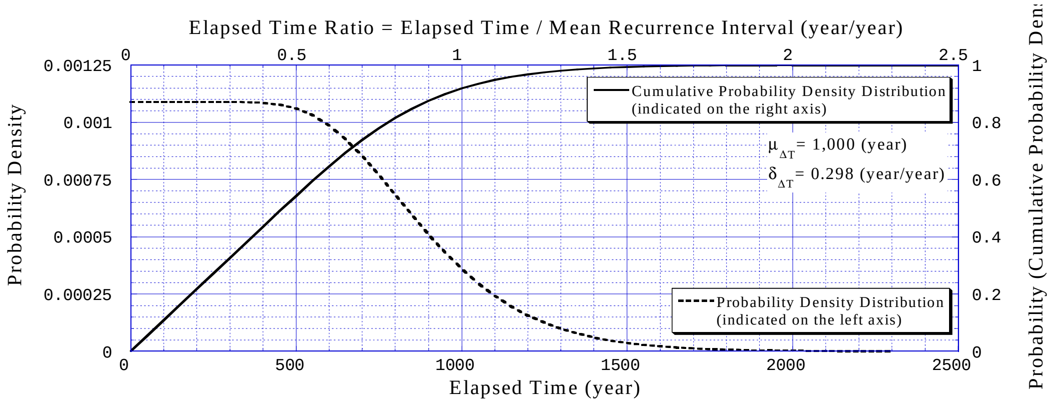


Figure 8 Probability Model of Elapsed Time (An example of Mean Recurrence Interval $\mu_{\Delta T}$ of 1000 year)

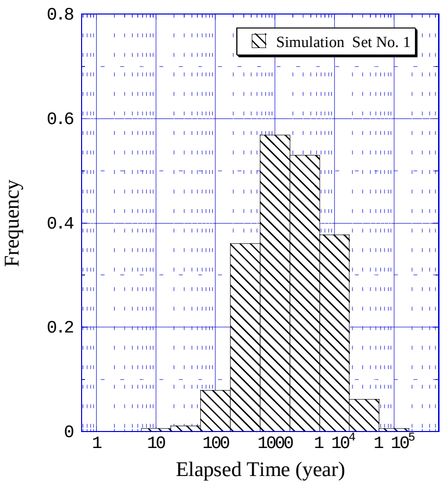


Figure 9 (a) Frequency of Elapsed Times (Set No. 1)

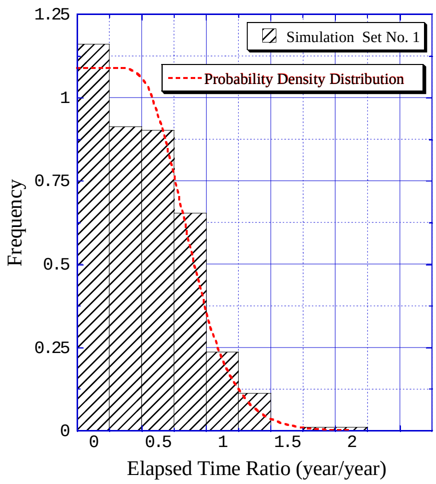


Figure 10 (a) Frequency of Elapsed Time Ratios (Elapsed Time/Mean Recurrence Interval) (Set No. 1)

The present paper does not take account of any interactions between active fault systems. There is a possibility of such interactions existing, and some researchers are studying the possibility of an “agitated period” and “tranquil period” related to intraplate earthquake occurrences. This may be influenced by the activity of plates moving near the Japanese archipelago, in that the activity of interplate earthquakes influences that of intraplate earthquakes. The authors do not deny these assumptions or possibilities here. However, recurrence intervals of interplate earthquakes are most likely shorter than 100 or 200 years, and such “agitated periods” and “tranquil periods” have not yet been recognised for terms as long as 400 years or more. Therefore, every elapsed time is simulated randomly due to the probability distribution in Figure 8 and, thus, independently to the others. The present paper discusses only long-term hazard assessment in Japan.

Simulations of Elapsed Times

Figures 9 and 10 show the result of simulations of elapsed times. Figure 9 shows the frequency distribution of the simulated elapsed times. As is clear from the figure, the elapsed times are distributed mainly between one hundred and ten thousand years. Figure 10 shows the ratios of elapsed times to their mean recurrence intervals (hereinafter “elapsed time ratios” *r*). As also shown in the figure, the frequency distribution of elapsed time ratios is in fair accord with the probability density distribution described in Figure 8, due to the large number of simulations.

Frequency of Earthquake Occurrences Obtained from the Simulated Elapsed Times of Δt≤400 Years, and Its Comparison with That of Historical Earthquakes

As the elapsed times are simulated for all active fault systems, the cumulative frequency of earthquake occurrences for each magnitude M_{JMA} can be calculated in the same way as those from historical record. Here, the cumulative frequencies are calculated by using the data of active fault systems whose elapsed times are simulated to be less than 400 years. Figure 11 shows a comparison between the commutative frequencies calculated by the simulations and those taken from historical record. The cumulative frequencies from historical record in Figures 6 and 11 are identical. As shown in the figures, the simulated frequencies in Figure 11 are more variable than those in Figure 6 because of the variation of simulating elapsed times. Specifically, some of the simulated cumulative frequencies are larger than those of historical record and others are smaller for most of M_{JMA}. Namely the cumulative frequencies of historical record are in fair accordance with those of the simulations.

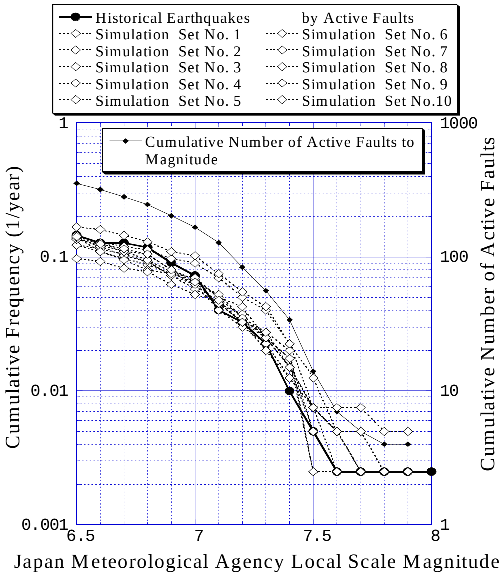


Figure 11 Simulated and Historical Cumulative Frequency of Earthquake Events vs. M_{JMA} (by Simulated Elapsed Times and Historical Record)

ESTIMATIONS OF 30-YEAR PROBABILITY OF EARTHQUAKE OCCURRENCE

Method of Obtaining Estimations

Here, distributions of the probabilities of earthquake occurrences within a 30-year period from the present time (hereinafter "30-year probabilities") are estimated. The simulated mean recurrence intervals $\mu_{\Delta T}$ in Chapter 2 and elapsed times Δt in Chapter 3 are used for the estimations. The reason for estimating 30-year probabilities is that lives of building structures are often prescribed to be 30 years in Japanese design codes. "100-year probabilities" and others can, however, also be estimated in the same way, as shown below.

The 30-year probability of each active fault system can be estimated due to eq.(2) as follows:

$$P_{30}\left(\Delta t \middle| \mu_{\Delta T}, \delta_{\Delta T}\right) = \int_{\Delta t}^{\Delta t+30} \{\text{eq.(2)}\} d\Delta T \Big/ \int_{\Delta t}^{\infty} \{\text{eq.(2)}\} d\Delta T \quad (12).$$

Estimations of 30-Year Probabilities by Eq.(12)

Figure 12 shows the relationship between probabilities and elapsed time ratios based on eq.(12). The probabilities are calculated for some representative mean recurrence intervals as indicated in the figure's legend. As clear from the figure, probabilities rapidly increase with elapsed time for any mean recurrence intervals where the elapsed time ratios r are small. The probabilities, however, do not increase much for any mean recurrence intervals where the elapsed time ratios r are larger than 0.7. More specifically, the figure shows that possibilities are small just after an earthquake event, and that the next event likely to occur at any time after r is greater than about 0.7. The number of active fault systems with large r, however, would not be very large. It can be noted from Figure 8 that r would be larger than 0.7 in one-quarter of all active fault systems, and that r would be larger than 1.5 in less than 1% of active fault systems. Figure 12 also shows that probabilities decrease as mean recurrence intervals increase for any elapsed time ratios. This is because the ratios of 30 years to mean recurrence intervals decrease as mean recurrence intervals increase. The maximum probability is about 0.25 for active fault systems with short mean recurrence intervals, and about 0.001 for those with long mean recurrence intervals.

Distributions of 30-Year Probabilities

Figure 13 shows the distribution of the estimated 30-year probabilities. The probabilities are arranged in order of increasing size. The larger probability is in the higher rank. As the figure shows one of the simulation results, the largest and/or the smallest probabilities may be different in every simulation. However, the shapes of distributions are almost the same in all ten simulation sets. Therefore, the following can be inferred:

(1) 30-year probabilities of one-third of all large active fault systems would be smaller than 10^{-8}.
(2) 30-year probabilities of half of all large active fault systems would be larger than 10^{-3}.

(3) 30-year probabilities of one-third of all large active fault systems would be larger than 10^{-2}.
(4) 30-year probabilities of about 10% of all large active fault systems would be larger than 0.03
(5) 30-year probabilities of very few large active fault systems would be larger than 0.10

It should also be noted that the shape of the distribution in the figure is down to the right hand side and downwardly convex. This means that a 30-year probability of one highly ranked active fault system is larger than that of many in the lowest ranked active fault systems. Accordingly, it is very effective to find out highly ranked (i.e. the most dangerous) active fault systems and to take countermeasures against those. Thus, trenching in-situ investigations etc. are very important as they enable us to identify such highly ranked active fault systems.

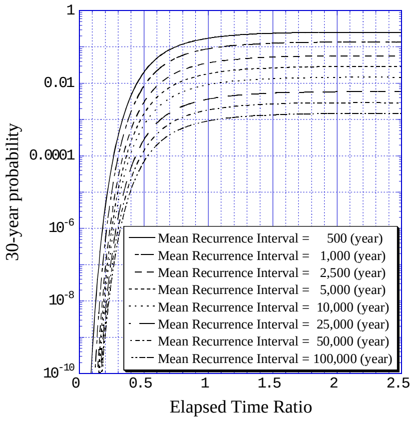


Figure 12 30-year Probability vs. Elapsed Time Ratio

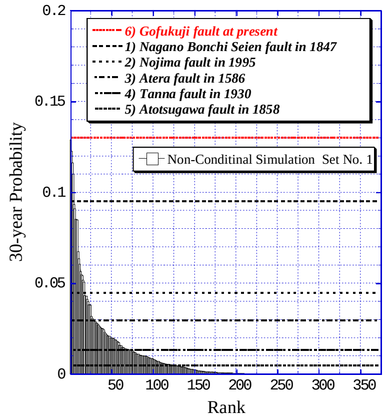


Figure 13 (a) 30-year Probabilities (Set No. 1)

Table 1. Probabilities of Earthquake Occurrences of Some Active Faults in the Historical Records

No	Fault Name	$\mu_{\Delta T}^{*}$	The Latest Earthquake		Elapsed Time	Elapsed Time Ratio	30-year probability (year for estimation)
		(year)	Earthquake Name	Year (A.D.)	(year)	(year/year)	(%)
1)	Nagano Bonchi Seien	1096	Zenkouji	1847	1112	1.01	9.3 (in 1847)
2)	Nojima	1556~2571	Hyogoken-Nanbu	1995	1938	0.75~1.25	3~6 (in 1995)
3)	Atera	1815	Tenshou	1586	1811	1.00	1.4~4.5 (in 1586)
4)	Tannna	1166	Kita-Izu	1930	895	0.77	1.3 (in 1930)
5)	Atotsugawa	2471	Hietsu	1859	1958	0.79	0.3~0.7 (in 1859)
6)	***Gofukuji***	***625~1184***	**Shinano**	***762 or 841***	**1155~1234**	**0.98~1.97**	***7~19 (at present)***

*Mean Recurrence Interval

Comparison of 30-Year Probabilities between the Simulations and Some Historical Earthquakes

Figure 13 also shows 30-year probabilities of some active faults where great historical earthquakes occurred. Table 1 shows them in detail. All numbers in the table were estimated by the subcommittee referred to in Chapter 1, though they sometimes use slightly different coefficients of variation in eq.(2). As shown in the table, the subcommittee estimated the 30-year probability just before the most recent event for active faults Nos. 1 to 5, and at present for No. 6. Some of the probabilities in Figure 13 are medians of those in Table 1. As evident in Figure 13, every 30-year probability in the table can be ranked highly. Here, it can be also noted that highly ranked active fault systems will not always be located near big cities. Thus, active faults in major city locations must be recognised as very dangerous when the 30-year probabilities are estimated as in Table 1.

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