Seismic Hazard Map Based on Active Faults and Past Earthquakes

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ABSTRACT

Past earthquake records have been primarily used for producing probabilistic seismic hazard maps, which depict peak ground acceleration or spectral response at various sites with a certain probability of exceedance during a specified time period. Those seismic hazard maps are applied to form regional classification maps in seismic design codes for various civil infrastructures in Japan, such as the Design Specifications for Highway Bridges. Regional seismicity is incorporated into determining seismic design motions based on regional classification.

Past earthquake records used for producing seismic hazard maps are based on instrumental observation and historical descriptions. Those earthquake records date back as long as one thousand and hundreds years, however they are still insufficient to evaluate seismic hazard due to active faults, because recurrence time intervals of these faults are generally estimated as several hundred to several thousand years.

In the present paper we discuss a procedure to evaluate seismic hazard based on past earthquake records, active faults and inter-plate earthquakes. Resultant seismic hazard maps are shown for central Japan. According to the numerical results, past earthquakes are generally influential in seismic hazards, however, the active faults with high occurrence rates of earthquakes and inter-plate earthquakes affect seismic hazards nearby, especially when a long period is assumed for analysis.

Key words: Probabilistic seismic hazard map, past earthquake records, active faults, inter-plate earthquakes

INTRODUCTION

Past earthquake records have been employed to produce probabilistic seismic hazard maps. In Japan past earthquake records include instrumental observation data during past one hundred years and historical description records during past one thousand and hundreds years. The period for which past earthquake records are available is not long enough to evaluate seismic hazard due to active faults, because their recurrence periods are estimated as several hundred to several thousand years.

In the present paper we assume three kinds of earthquakes, i.e. earthquakes that occur randomly in both time and space, earthquakes from causative active faults and inter-plate earthquakes. We first discuss a procedure to evaluate seismic hazard due to each kind of earthquakes. Secondly we discuss a procedure to integrate seismic hazard related to each kind of earthquakes into the comprehensive seismic hazard caused by all three kinds of earthquakes.

We develop seismic zones in which uniform

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seismicity is assumed individually, using broad geologic criteria and seismicity data around Japan. Various-scale earthquakes are assumed to occur randomly in both time and space within these seismic zones. On the other hand, specific recurrence time intervals and magnitudes are assumed for earthquakes caused by active faults and inter-plate earthquakes. When the occurrence time of the latest event is known for these earthquakes, we employ a time-dependent model for earthquake occurrence, otherwise we assume a time-independent model.

SEISMIC HAZARD BASED ON PAST EARTHQUAKE RECORDS

Earthquake Catalogs

Earthquake catalogs adopted in the present study are as follows:

-Usami Catalog (1996) for 416-1884
-Utsu Catalog (1987) for 1885-1925
-Japan Meteorological Agency (JMA) Catalog for 1/1926- 7/1996

Figs.1(a) and (b) show cumulative distributions of earthquake records for events with JMA magnitude Mj＜6.0 and Mj≧6.0, respectively. Since evident accumulation of earthquake records can be found from 1926 and 1885 for Mj ＜ 6.0 and Mj ≧ 6.0, respectively, we incorporate the following catalogs into analysis:

- JMA Catalog for Mj＜6.0
- Utsu and JMA Catalogs for Mj≧6.0

Fig.2 shows the epicenters of above-mentioned past earthquakes. Note that the inter-plate earthquakes are excluded from Fig.2, because those earthquakes are separately considered from past earthquakes in our analysis.

Seismic Zone and Earthquake Occurrence Characteristics

Based on seismotectonics around Japan after Hagiwara(1991), we develop seismic zones in which uniform seismicity is assumed individually. Gutenberg-Richter relationship given by eq.(1) is assumed to represent frequency distribution of earthquake magnitude for each seismic zone.

$$\log Ni\,[M>m] = a_i - b_i\, m \tag{1}$$

where,

Ni: Number of earthquakes per year with magnitude greater than m within i-th seismic zone

a_i, b_i: Coefficients for i-th seismic zone

Earthquake occurrence rate per year and area in i-th seismic zone is computed as

$$\nu_i = \frac{10^{a_i - b_i Mi_L}}{A_i} \tag{2}$$

where,

νi: Mean earthquake occurrence rate per year and area in i-th seismic zone

Mi_L: Minimum magnitude of earthquake considered in analyses.(= 5.0)

Ai: Area of i-th seismic zone

Probability density function of magnitude is derived from eq.(1) as

$$fi_M(m) = \frac{b_i \exp[-b_i (m - Mi_L)]}{1 - \exp[-b_i (Mi_U - Mi_L)]} \tag{3}$$

where,

$fi_M(m)$: Probability density function of magnitude

Mi_U: Possible maximum magnitude in i-th seismic zone

Based on earthquake records within i-th seismic zone, a_i and b_i–values are determined by least squares fit as shown in Table 1. Hagiwara(1991) compared the maximum magnitude of past earthquakes and that of earthquakes from active faults in each seismotectonic zone, and adopted the larger one as the maximum magnitude in the zone. Based on Hagiwara (1991), we assume the maximum magnitude in each seismic zone as shown in Table 1.

Ground Motion Attenuation Relation with Distance

Peak ground acceleration (PGA) is estimated by attenuation relation after Annaka et al.(1988), which is given by eq.(4), in the present study. Their attenuation relation was derived from data on the outcropped bedrock whose shear wave velocity is larger than 300m/sec. Although they use the shortest distance to a fault plane as a distance parameter, we substitute epicentral distance for the shortest distance. Average depth of focus in each seismic zone is used as focal depth parameter in the attenuation relation.

$$\log X = 0.627M + 0.00671H - 2.212\log(R + 0.35e^{0.65M}) + 1.711 \quad (4)$$

where,
X: PGA [gal]
M: Magnitude
H: Focal Depth [km]
R: Shortest distance between site and fault plane [km]

For incorporating the scatter of ground motion estimated by attenuation relation into analysis, $\pm 2\sigma$ variation around mean value is considered, where σ represents a standard variation of attenuation equation.

Suppose an earthquake with magnitude m occurs at a distance r from the site, probability that PGA X exceeds a specific level x is expressed as

$$P x_i[X > x \mid m, r] = \int_X^\infty fx_i(X \mid m, r)dX \quad (3)$$

where,
$fx_i(X|m,r)$: Probability density function of PGA generated by an earthquake with magnitude m at a distance r.
m: Magnitude
r: Shortest distance between site and fault plane [km]

Hazard Evaluation Based on Past Earthquake Records

Combining eqs.(2), (3) and (5), probability that PGA X exceeds x during a period of T_D can be given by eq.(6).

$$P_h[X > x \mid T_D] = 1 - (1 - \lambda)^{T_D} \quad (6)$$

$$\lambda = \int_A \int_{M_L}^{Mi_U} fi_M(m) P x_i[X > x \mid m, r] \frac{\nu_i}{A_i} dmds \quad (7)$$

where,
$P_h[X>x|T_D]$: Probability that PGA X exceeds x during a period of T_D
T_D: Period [year]
λ: Probability of exceedance of x at a site during a year

SEISMIC HAZARD BASED ON ACTIVE FAULTS

Active Faults for Analysis

We employ the following two kinds of active faults for analysis.
(1) Seismogenic faults after Matsuda(1990): Active faults or groups of active faults that

may produce independent large earthquakes

(2) Active faults with length of 10km or longer, which are not categorized as seismogenic faults (Research group for active faults, 1990)

Active faults categorized in (2) are also assumed to generate an independent event as faults in (1). Fig.4 shows locations of seismogenic and active faults.

Magnitudes and Occurrence rates

Matsuda (1975) derived relationships among fault length, dislocation and earthquake magnitude as eqs. (8) and (9). Introducing an average slip rate of fault, we can evaluate average recurrence period by eq. (10). When an average slip rate is given by range, we use the central value of range.

$$M_j = (\log(L_j) + 2.9) / 0.6 \qquad (8)$$

$$M_j = (\log(D_j)+4.0) / 0.6 \qquad (9)$$

$$\log(T_{Rj}) = \log(L_j / \nu_j)+1.9 \qquad (10)$$

where,
M_j: Magnitude
L_j: Fault length [km]
D_j: Dislocation of fault rupture [m]
T_{Rj}: Average recurrence period [year]
ν_j: Average slip rate [m/year]

The Headquarters for Earthquake Research Promotion was installed by Prime Minister’s office after the 1995 Kobe Earthquake. The Headquarters is promoting survey at 98 major active faults. Geological Survey of Japan and Ministry of Education, Culture, Sports, Science and Technology also conduct surveys. We incorporate newly obtained information by those surveys into analysis.

When the occurrence time of the latest event is known, in addition to the average recurrence period, we assume a time-dependent stochastic process model for earthquake occurrence, which is given by eq.(11) after Okumura(1996). We use a logarithmic normal distribution for this model. The Headquarters for Earthquake Research Promotion (1999) suggested the standard deviation of this distribution as 0.23. When the occurrence time of the latest event is unknown, we employ stationary Poisson process for earthquake occurrence as shown by eq.(12).

$$P_j[T_D] = \frac{F_j(t_{0j}+T_D)-F_j(t_{0j})}{1-F_j(t_{0j})} \qquad (11)$$

$$P_j[T_D] = 1-e^{-\frac{T_D}{T_{Rj}}} \qquad (12)$$

where,
$P_j[T_D]$: Probability of earthquake occurrence
t_{0j}: Elapsed time from the last event [year]
T_D: Time interval to calculate probability of earthquake occurrence [year]
T_{Rj}: Average recurrence period [year]

Fig.5 shows the relation between earthquake occurrence probability during 50 years and elapsed time from the last occurrence, in which logarithmic normal distribution is employed. Note that the probability of earthquake occurrence increases as the elapsed time from the last event becomes approximately two times of the average recurrence period, and then the probability decreases. This phenomenon is attributed to the characteristics of logarithmic normal distribution, and we truncate the probability of earthquake occurrence at two times of the average recurrence period.

Ground Motion Attenuation Relation with Distance

We employ ground motion attenuation relation after Annaka et al.(1988) for hazard analysis based on active faults the same as the case of past earthquake records. The shortest distance to a fault line is used as distance parameter and focal depth is assumed to be 0 [km].

Similar to eq.(5), probability that PGA X exceeds a specific level x due to an earthquake generated by an active fault is written as eq. (13).

$$Px_j[X > x \mid M_j, r] = \int_X^\infty fx_j(X \mid M_j, r)dX \qquad (13)$$

Hazard Evaluation Based on Active Faults

Using eqs. (11)-(13), we can calculate probability that PGA X exceeds x during T_D years due to all the active faults by eq.(14).

$$P_f[X > x, T_D] = 1 - \prod_j \{1 - P_{f\,j}[X > x, T_D]\} \quad (14)$$

$$P_{f\,j}[X > x, T_D] = P_j[T_D]Px_j[X > x \mid M_j, r] \quad (15)$$

SEISMIC HAZARD BASED ON INTER-PLATE EARTHQUAKE

Inter-Plate Earthquakes for Analysis

Large-scale earthquakes that occur in the Sagami, Suruga and Nankai trough regions are considered as inter-plate earthquakes in this study. Inter-plate earthquakes occurred in Sagami trough region, and Suruga and Nankai trough regions are called the Kanto earthquake and the Tokai-Nankai earthquake, respectively.

Fault Planes, Magnitudes, Recurrence Periods

We establish fault planes, magnitudes and average recurrence periods for the Tokai-Nankai earthquake and the Kanto earthquake based on the earthquakes shown in Table 3. The Ansei Tokai Earthquake on 12/23/1854 and the Ansei Nankai Earthquake on 12/24/1854 are assumed to occur at the same time. In addition, the Tonankai Earthquake in 1944 and the Nankai Earthquake in 1946 are also assumed to occur at the same time, i.e. 1944. Average recurrence period of the Tokai-Nankai earthquake are evaluated as 119 years. Fig.7 shows fault planes and magnitudes of past Tokai-Nankai earthquakes. Note that we assume the same magnitude Mj=8.4 for two events in 1854 and Mj=8.0 for events in 1944 and 1946. As shown in Fig.6, there are three patterns for the Tokai-Nankai earthquake, and we assume each pattern has the same probability to occur, i.e. 33.3%.

Average recurrence period of the Kanto earthquake is evaluated as 220 years based on Table 3. The last Kanto earthquake occurred in 1923. Similar to the case of the Tokai-Nankai earthquake, we assume two patterns, which are shown in Fig.7, and each pattern has 50% probability to occur.

For evaluating occurrence rate of the Tokai-Nankai earthquake and the Kanto earthquake logarithmic normal distribution function for recurrence period is employed.

Ground Motion Attenuation Relation

Eq.(4) is used for inter-plate earthquakes, also. The shortest distance to fault planes is employed as distance parameter. Depth of the point on a fault plane that yields the shortest distance to the site is used as focal depth in the attenuation relation.

Hazard Evaluation Based on Inter-plate Earthquakes

Similar to the case of hazard analysis based on active faults, we can calculate probability that PGA X exceeds x during T_D years due to all inter-plate earthquakes by eq.(16).

$$P_p[X > x, T_D] = 1 - \prod_i \{1 - P_{p_i}[X > x, T_D]\} \quad (16)$$

$$P_{p_i}[X > x, T_D] = P_i[T_D] Px_i[X > x \mid m_i, r] \quad (17)$$

$$Px_j[X > x \mid M_j, r] = \int_X^\infty fx_j(X \mid M_j, r)dX \quad (18)$$

where,

$P_{p_i}[X > x, T_D]$: Probability that PGA X exceeds x during T_D years due to a specific inter-plate earthquake

$Px_j[X > x \mid M_j, r]$: Probability that PGA X exceeds a specific level x due to an earthquake generated by an inter-plate earthquake

SEISMIC HAZARD BASED ON PAST EARTHQUAKE RECORDS, ACTIVE FAULTS AND INTER-PLATE EARTHQUAKES

We calculate comprehensive seismic hazard due to past earthquakes, active faults and inter-plate earthquakes by eq.(19) on the assumption that these three earthquake sources are independent each other.

$$P[X > x, T_D] = 1 - (1 - P_h[X > x \mid T_D])(1 - P_f[X > x, T_D])(1 - P_p[X > x, T_D]) \quad (19)$$

where,

$P_h[X>x|T_D]$: Probability that ground motion X from seismic zones exceeds x during T_D years

$P_f[X>x|T_D]$: Probability that ground motion X from active faults exceeds x during T_D years

$P_p[X>x|T_D]$: Probability that ground motion X from inter-plate earthquakes exceeds x during T_D years.

RESULTS

Seismic Hazard Map Based on Past Earthquakes

Seismic hazard maps based on past earthquake records are shown in Fig.8. Figs.8(a) and (b) show PGA with 39.5% probability of exceedance during 50 years and that with 39.4% probability of exceedance during 500 years, respectively. These conditions correspond to return periods of approximately 100 and 1000 years. As the uncertainties associated with ground motion estimation, we assume ±2σ variation around mean value deduced by attenuation relation. In both figures, large PGA appears in the southern Kanto region and in the southern coast of Chubu region.

Seismic Hazard Map Based on Active Faults

Fig.9 shows seismic hazard maps based on active faults. Fig.9(a) and (b) present PGA with 39.5% probability of exceedance during 50 years and that with 39.4% probability of exceedance during 500 years, respectively. Fig.10 shows probability of earthquake occurrence due to seismogenic faults and active faults during 50 and 500 years. In Fig.9(a) we find that PGA is large in midway areas between two active faults with high occurrence rates, such as Itoigawa-Shizuokakozosen fault systems and Fujikawakako faults group, Kitatake faults group and Kamogawatikotai-north/south fault. Each of these faults does not exert influence upon calculation result, because probabilities of earthquake occurrence due to these faults during

50 years are less than 39.5%. It is deducible that these active faults synergistically affect seismic hazard over midway areas among them.

In Fig.9 (b) PGA is large around active faults with high probability of earthquake occurrence for 500 years, such as Tenpakukako fault, Kokuhu faults group, Sekiya fault in addition to faults that have high probability of earthquake occurrence even for 50 years, such as Itoigawa-Shizuokakozosen fault systems, Fujikawakako faults group.

Seismic Hazard Map Based on Inter-Plate Earthquakes

Fig.11 shows the accumulation of probabilities that Kanto and Tokai-Nankai earthquakes occur with passage of time from the present. Occurrence probabilities of Kanto and Tokai-Nankai earthquakes during next 50 years are about 1% and 30%, respectively. Each earthquake itself has no influence on PGA with 39.5% probability of exceedance during 50 years, because the earthquake occurrence probability during 50 years is less than 39.5%. PGA with 39.4% probability of exceedance during 500 years is calculated as shown in Fig.12. Reflecting fault locations, large PGA distribute along the southern coasts of Kanto and Chubu regions.

Seismic Hazard Map Based on Past Earthquake Records, Active Faults and Inter-Plate Earthquakes

Fig.13 presents seismic hazard maps in which past earthquakes, active faults and inter-plate earthquakes are incorporated. Results are shown for PGA with 39.5% probability of exceedance during 50 and that with 39.4% probability of exceedance during 500 years. Similar to the previous results, $\pm 2\sigma$ variation is added to the expected value by attenuation relation. Comparing Fig.13(a) and Fig.8(a), which correspond to 39.5% probability of exceedance during 50 years, we find that past earthquake records generally control the result, and that active faults with high probability of earthquake occurrence, such as Itoigawa-Shizuokakozosen fault systems, Fujikawakako faults group, Kitatake faults group are influential in midway areas between them.

In case of Fig.13(b), influence of active faults become large, comparing to the case of Fig.13(a). Active faults, such as Itoigawa-Shizuokakozosen fault systems, Fujikawakako faults group, Tenpakukako fault, Kokuhu faults group, Sekiya fault, generate large PGA around them. The inter-plate earthquakes also have large influence upon seismic hazard along coastal areas.

CONCLUSIONS

We incorporate three kinds of earthquakes, i.e., earthquakes that occur randomly in both time and space, earthquakes from active faults and inter-plate earthquakes into seismic hazard analysis. Seismic hazard due to each kind of earthquake is evaluated. Assuming that each kind of earthquake occurs independently, a joint seismic hazard due to three sources is also estimated. Results are shown for PGA with 39.5% probability of exceedance during 50 years and that with 39.4% probability of exceedance during 500 years. The following conclusions may be deduced from the present study.

1) Seismic hazard based on past earthquake records is generally dominant over PGA with 39.5% probability of exceedance during 50 years. Active faults with high

earthquake occurrence probabilities during 50 years are exceptionally influential in nearby areas.

2) For PGA with 39.4% probability of exceedance during 500 years, the influence of active faults becomes distinct. Large PGA is obtained near the active faults with high earthquake occurrence probabilities.

3) Inter-plate earthquakes affect much the seismic hazard along coastal regions when 39.4% of probability of exceedance during 500 years is assumed.

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Table1 Excluded Inter-plate Earthquakes from Past Earthquake Records

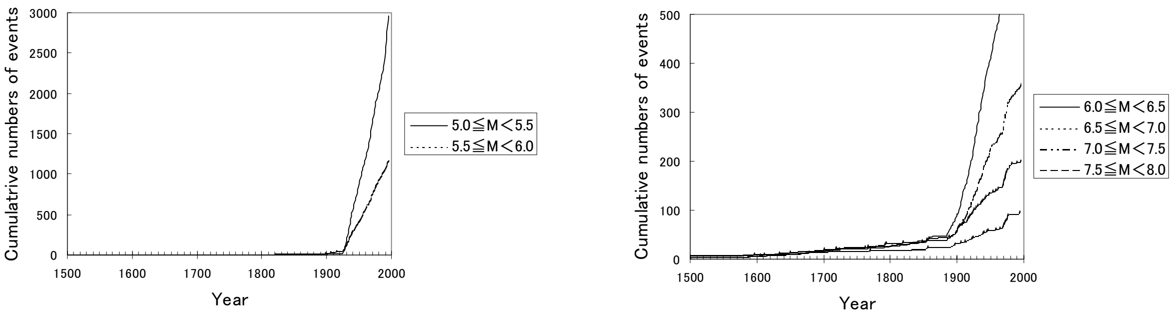
	Occurrence date	Mj
Tonankai earthquake	12/7/1944	7.9
Nankai earthquake	12/21/1946	8.0
Kanto earthquake	9/1/1923	7.9

Table2 Earthquake Occurrence Modeling for Each Seismic Zone

Seismic Zone	Number of Earthquake Records	Maximum Magnitude	Average Focal Depth (km)	a-value	b-value	Yearly Earthquake Occurrences Rate
21	1572	8.2	40.9	5.12	0.79	15.300
22	2243	8.55	31.6	4.42	0.67	11.200
31	136	7.1	46.4	4.78	0.90	1.900
32	159	7.5	44.3	5.19	0.92	3.830
33	191	7.5	43.6	5.64	1.02	3.410
41	212	7.75	15.4	7.39	1.27	11.100
42	22	7.75	12.7	3.36	0.74	0.435
51	254	8.2	38.6	4.25	0.75	3.090
61	184	7.3	23.1	4.93	0.91	2.310
62	9	7.3	39.3	3.49	0.86	0.160
71	39	8.4	14.6	4.18	0.80	1.530
72	34	8.4	13.9	3.50	0.67	1.370
73	378	7.75	36.5	5.16	0.88	5.680
81	47	8	13.5	5.61	1.12	1.060
82	93	8	24.3	4.59	0.87	1.780
83	189	8	30.1	4.63	0.87	1.940
91	38	7.75	12.1	4.80	0.96	1.000
92	112	7.75	20.2	5.21	0.93	3.850
93	172	7.25	32.6	3.31	0.59	2.270
101	179	8	6.7	5.02	0.89	3.670
102	1	7	0.0	0.00	0.00	0.000
111	22	7	23.6	4.33	0.93	0.477
112	3	7.75	34.3	2.06	0.66	0.056
121	303	7.3	45.8	5.12	0.92	3.250

Table3 Kanto Earthquakes and Tokai-Nankai Earthquakes

Earthquakes in analysis	Past earthquakes	Occurrence date	Mj
Tokai-Nankai earthquake	Hoeitokai-Nankai earthquake	10/28/1707	8.4
	Anseitokai earthquake	12/23/1854	8.4
	Anseinankai earthquake	12/24/1854	8.4
	Tonankai earthquake	12/7/1944	7.9
	Nankai earthquake	12/21/1946	8.0
Kanto earthquake	Genrokukanto earthquake	12/31/1703	8.2
	Taishokanto earthquake	9/1/1923	7.9



(a) Mj＜6.0 (b) Mj≧6.0

Fig.1 Cumulative Distribution of Earthquake Records

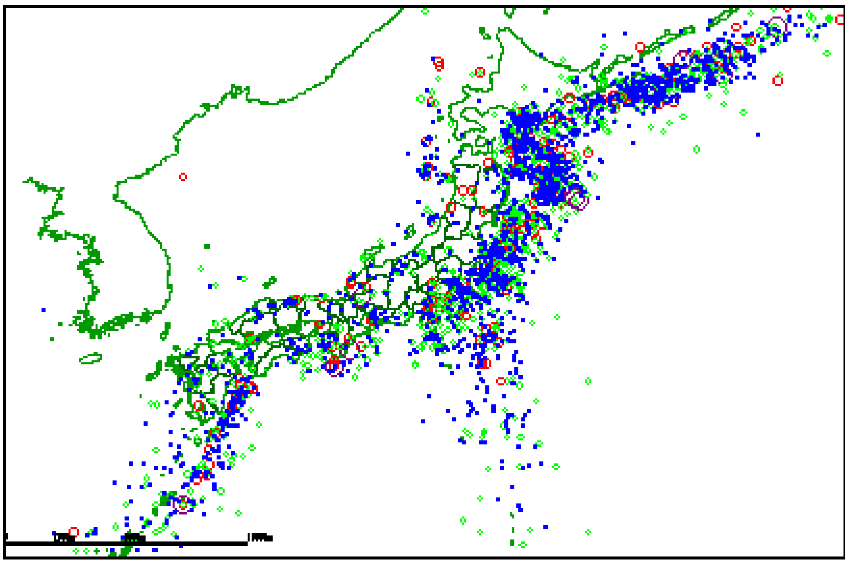


Fig. 2 Epicenters of Past Earthquakes

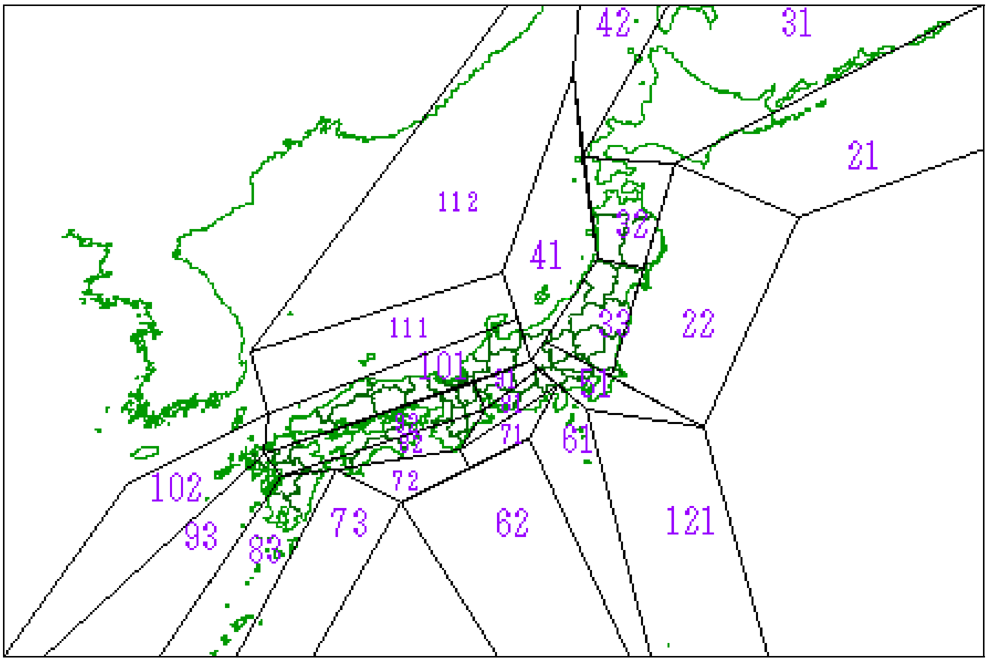


Fig.3 Seismic Zones

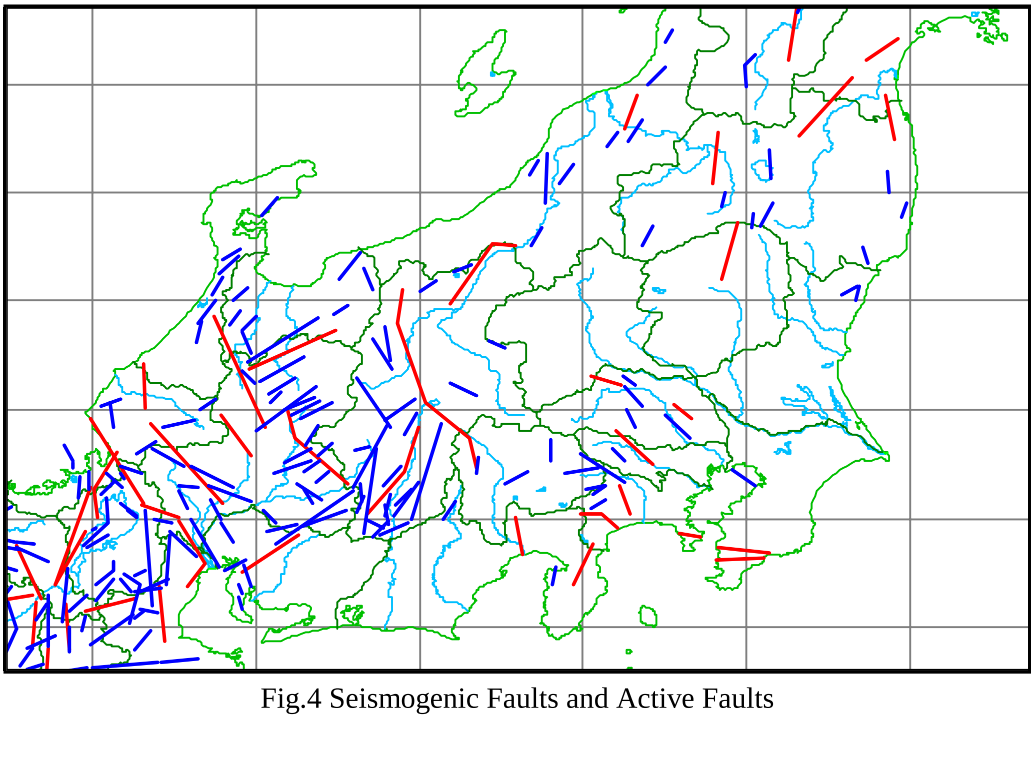


Fig.4 Seismogenic Faults and Active Faults

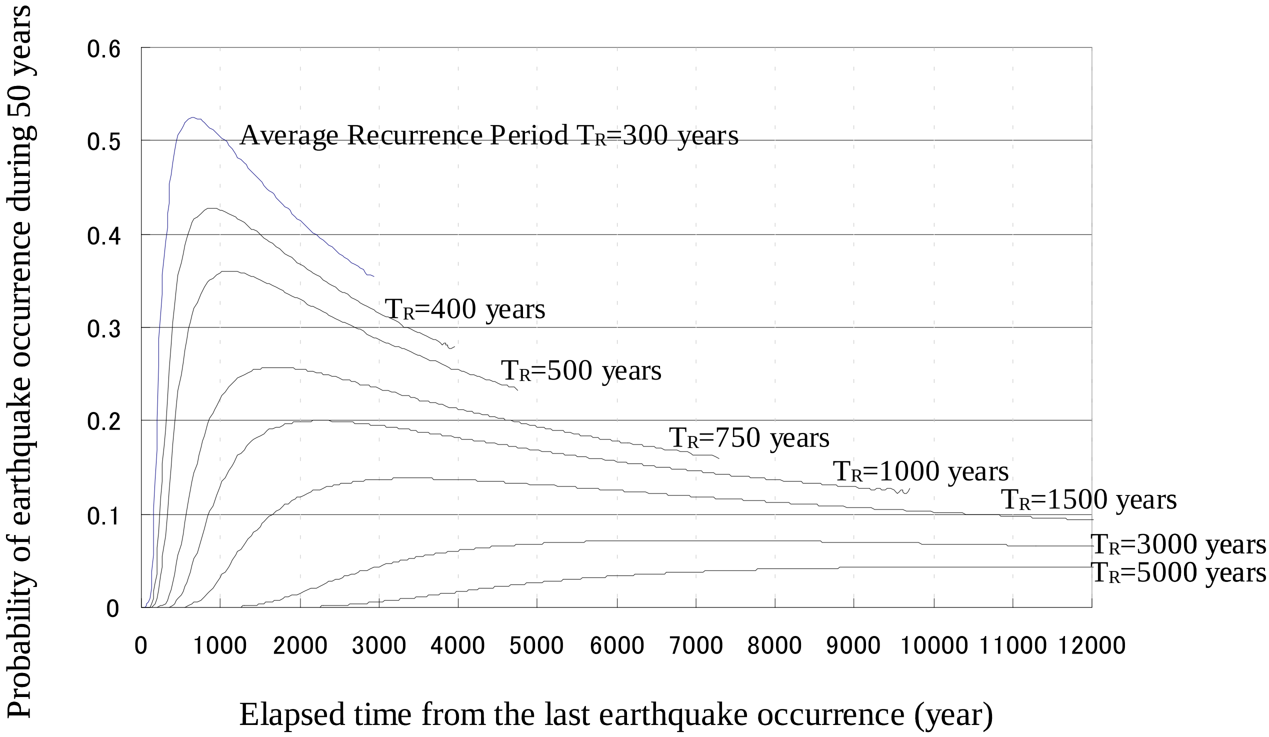
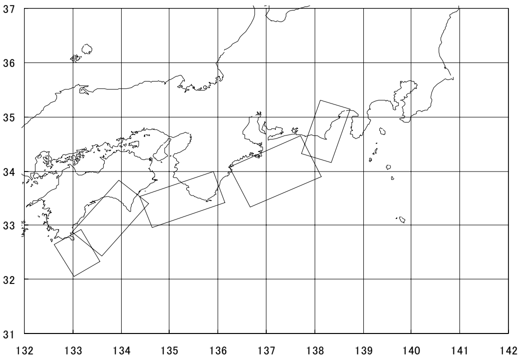
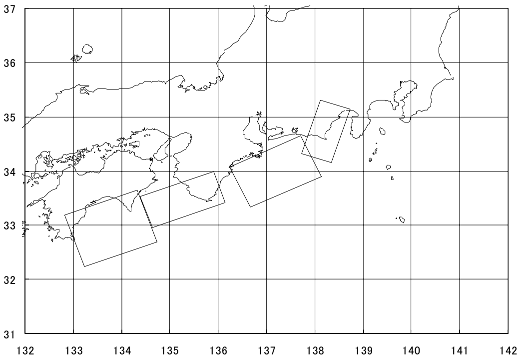


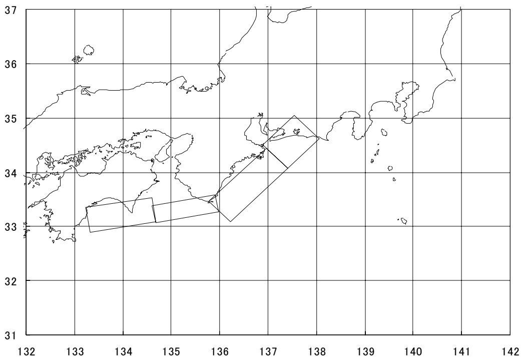
Fig.5 Relation Between Probability of Earthquake Occurrence and Elapsed Time from the Last Event



(a) Mj=8.4 (1707)

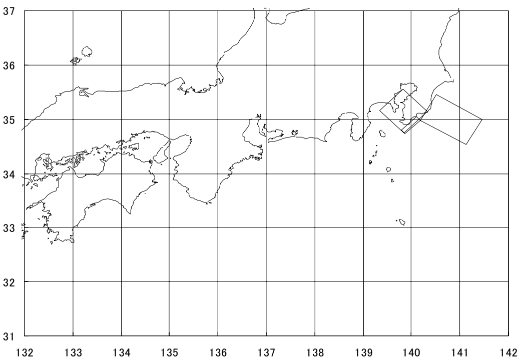


(b) Mj=8.4 (1984)

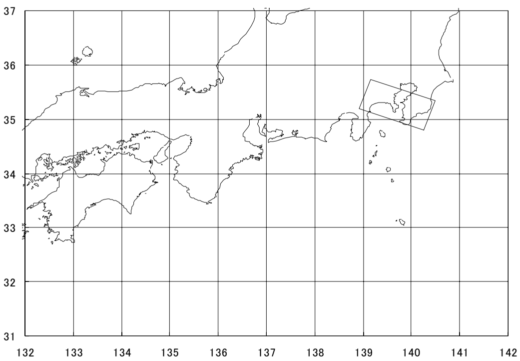


(c) Mj=8.0 (1944)

Fig. 6 Tokai-Nankai Earthquakes

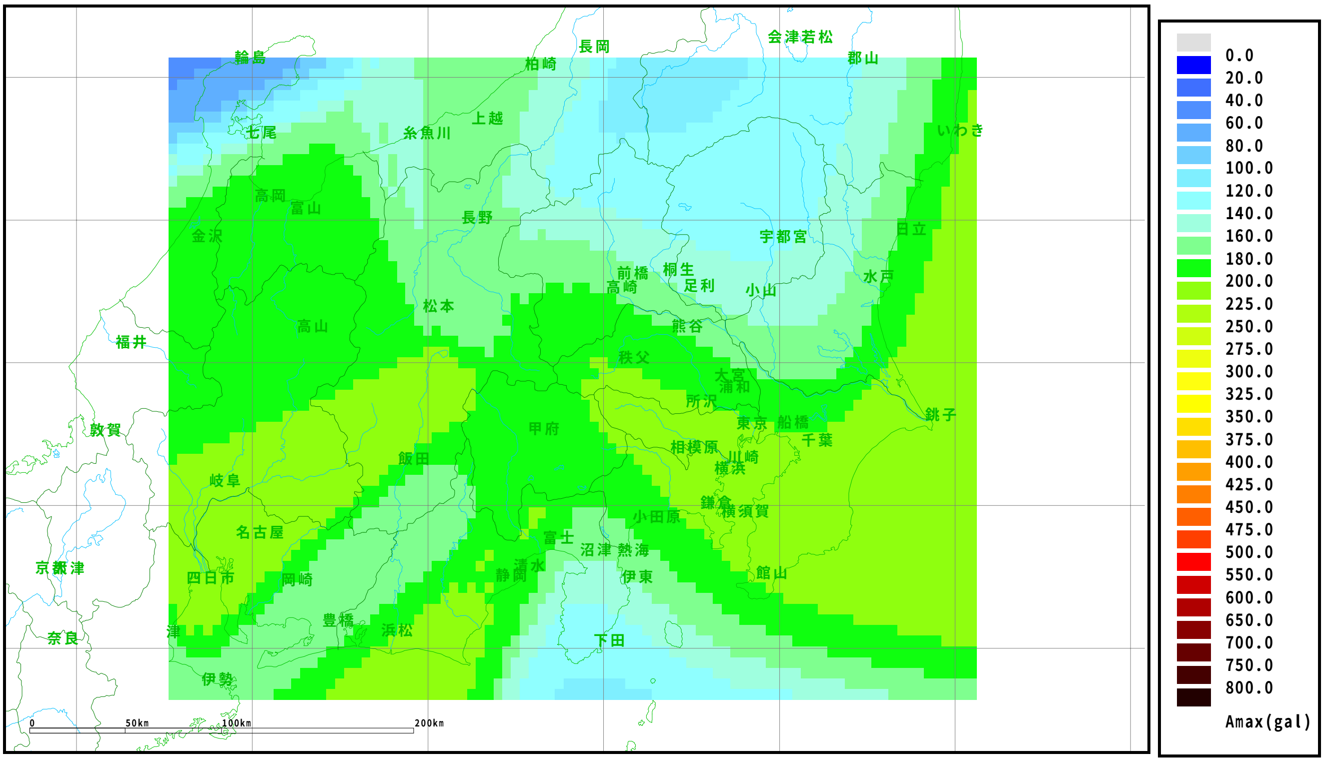


(a) Mj=8.2 (1703)

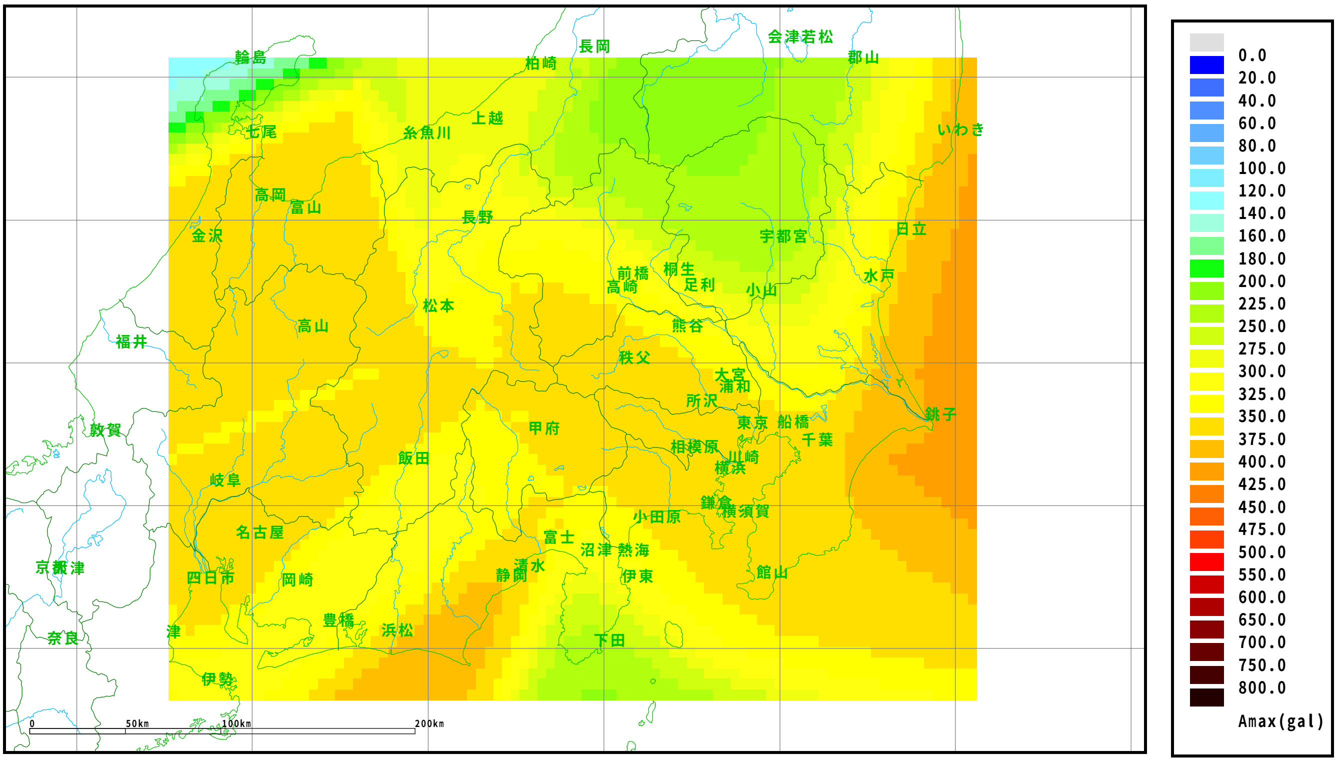


(b) Mj=7.9 (1923)

Fig. 7 Kanto Earthquakes

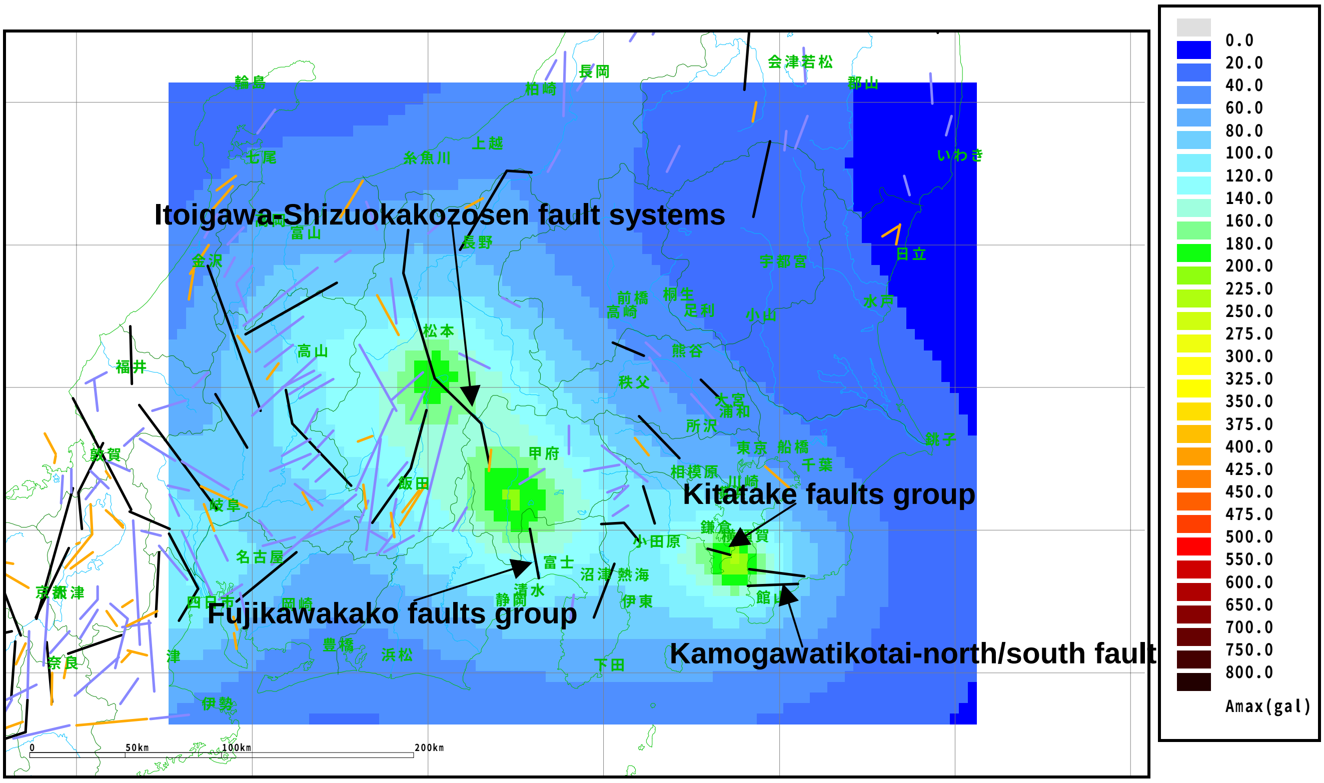


(a) PGA with 39.5% Probability of Exceedance during 50 Years

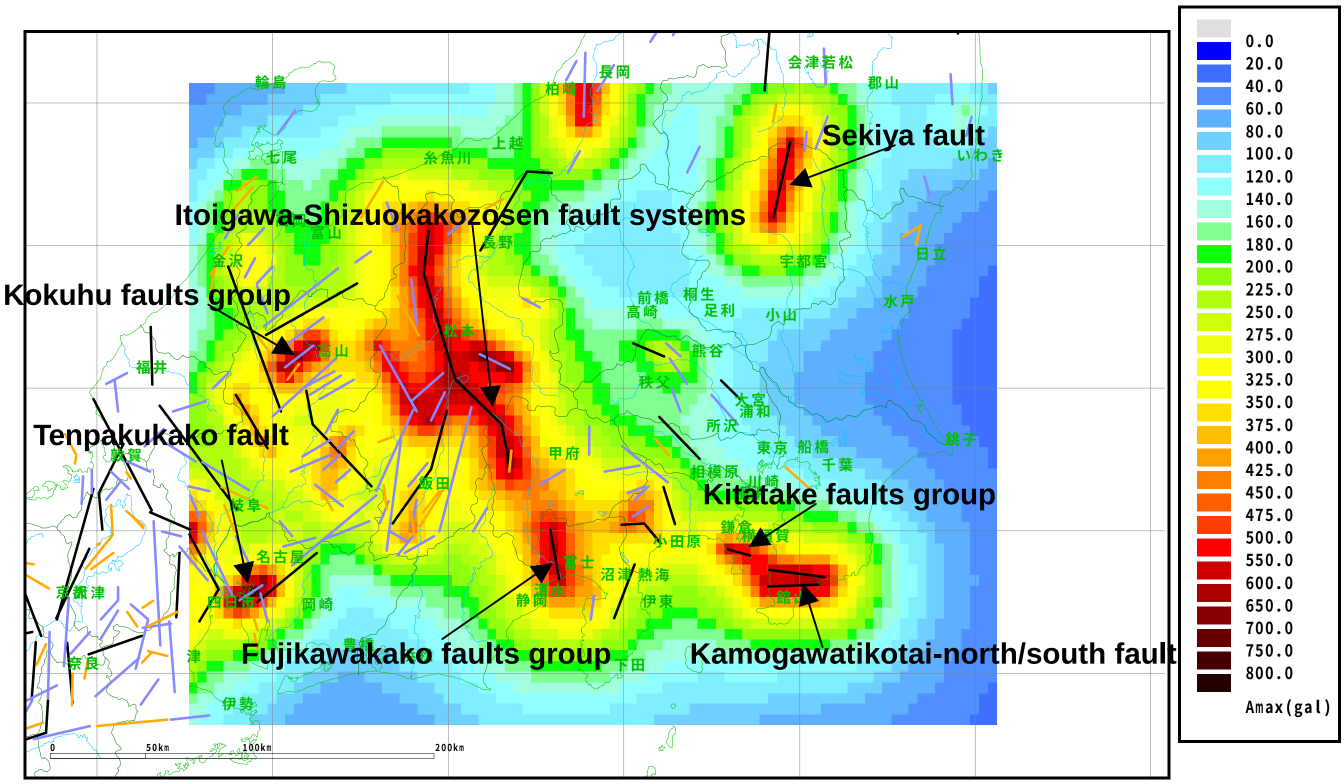


(b) PGA with 39.4% Probability of Exceedance during 500 Years

Fig.8 Seismic Hazard Map Based on Past Earthquake Records

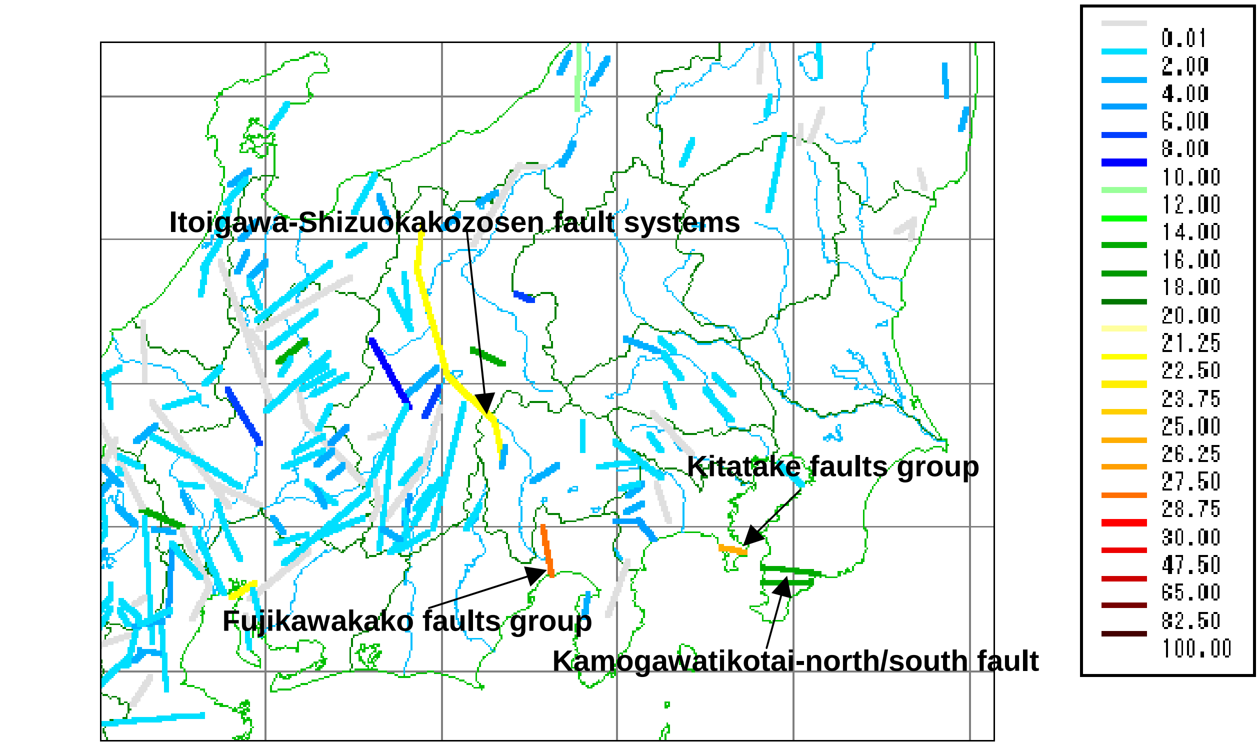


(a) PGA with 39.5% Probability of Exceedance during 50 Years

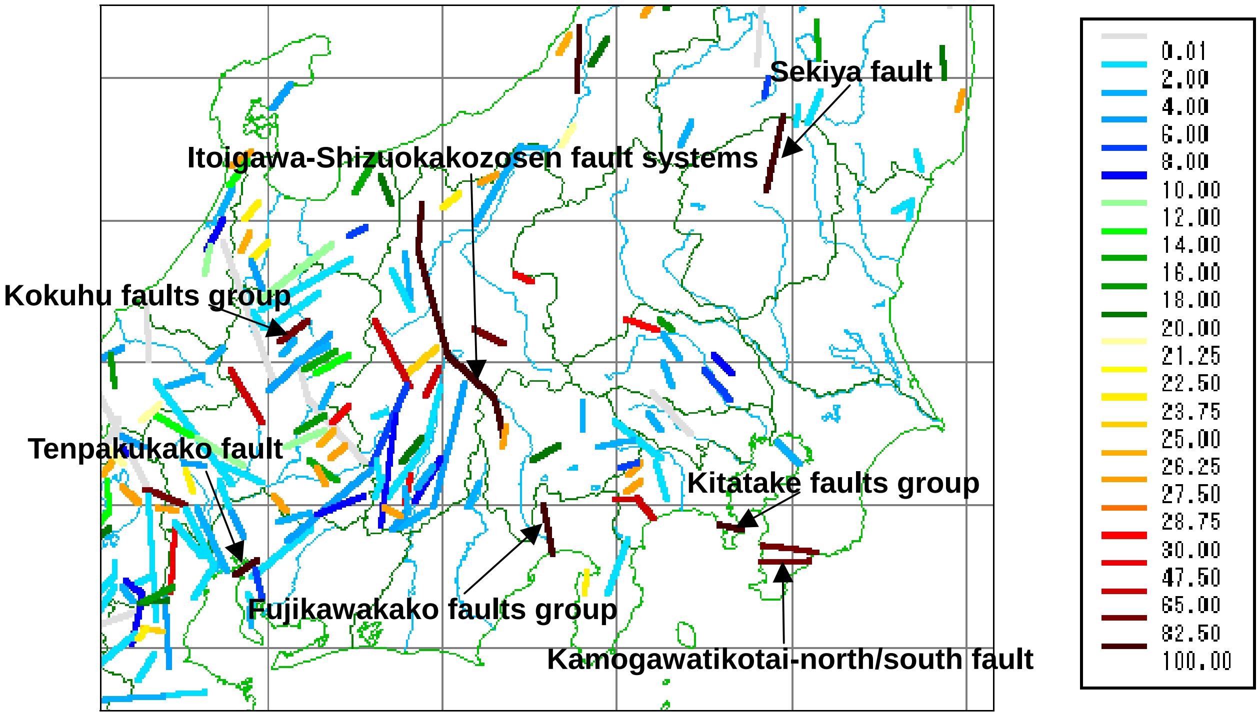


(b) PGA with 39.4% Probability of Exceedance during 500 Years

Fig.9 Seismic Hazard Map Based on Active Faults



(a) Earthquake Occurrence Probabilities during 50 Years



(b) Earthquake Occurrence Probabilities during 500 Years

Fig.10 Earthquake Occurrence Probabilities of Active Faults

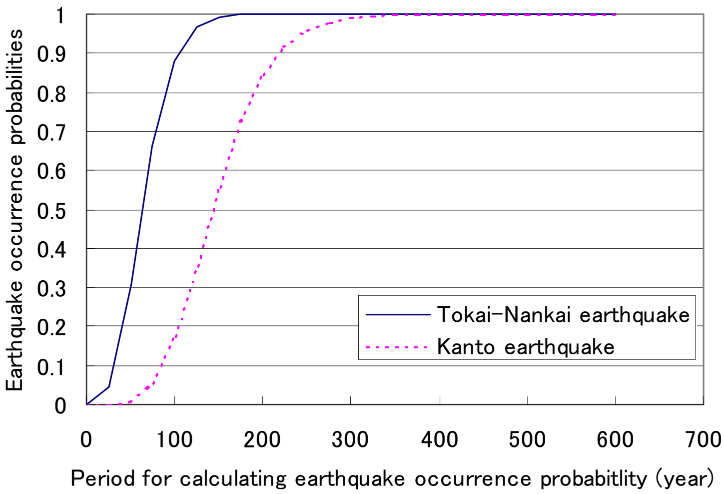


Fig.11 Occurrence Probabilities of Inter-plate Earthquakes for 500 Years

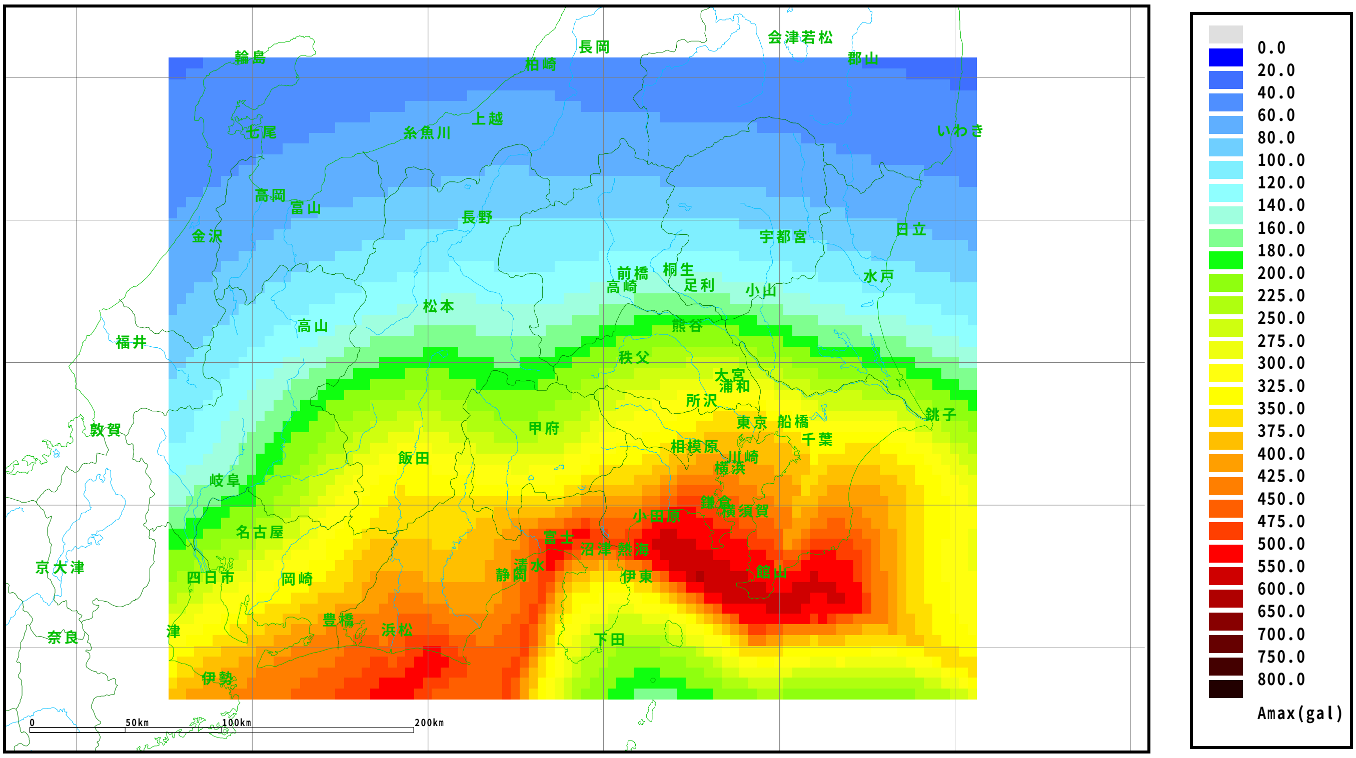
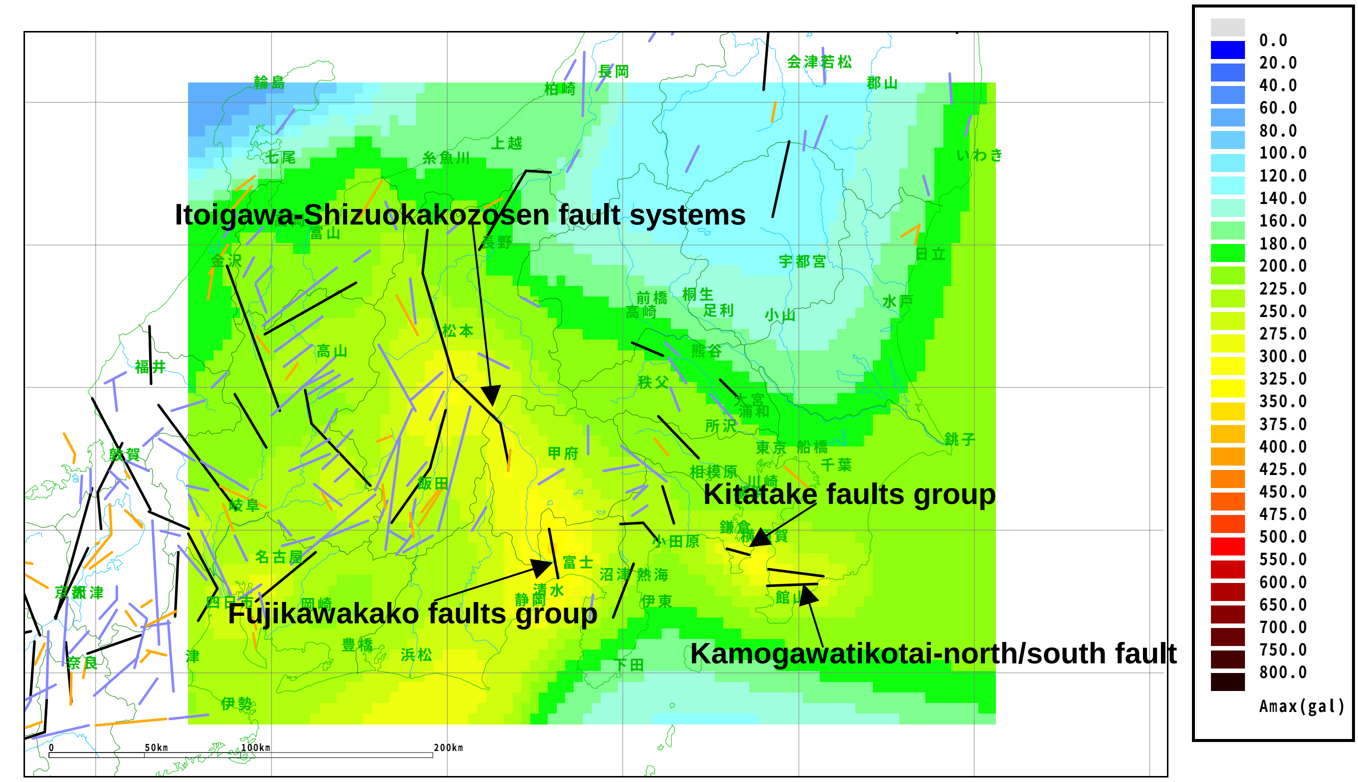
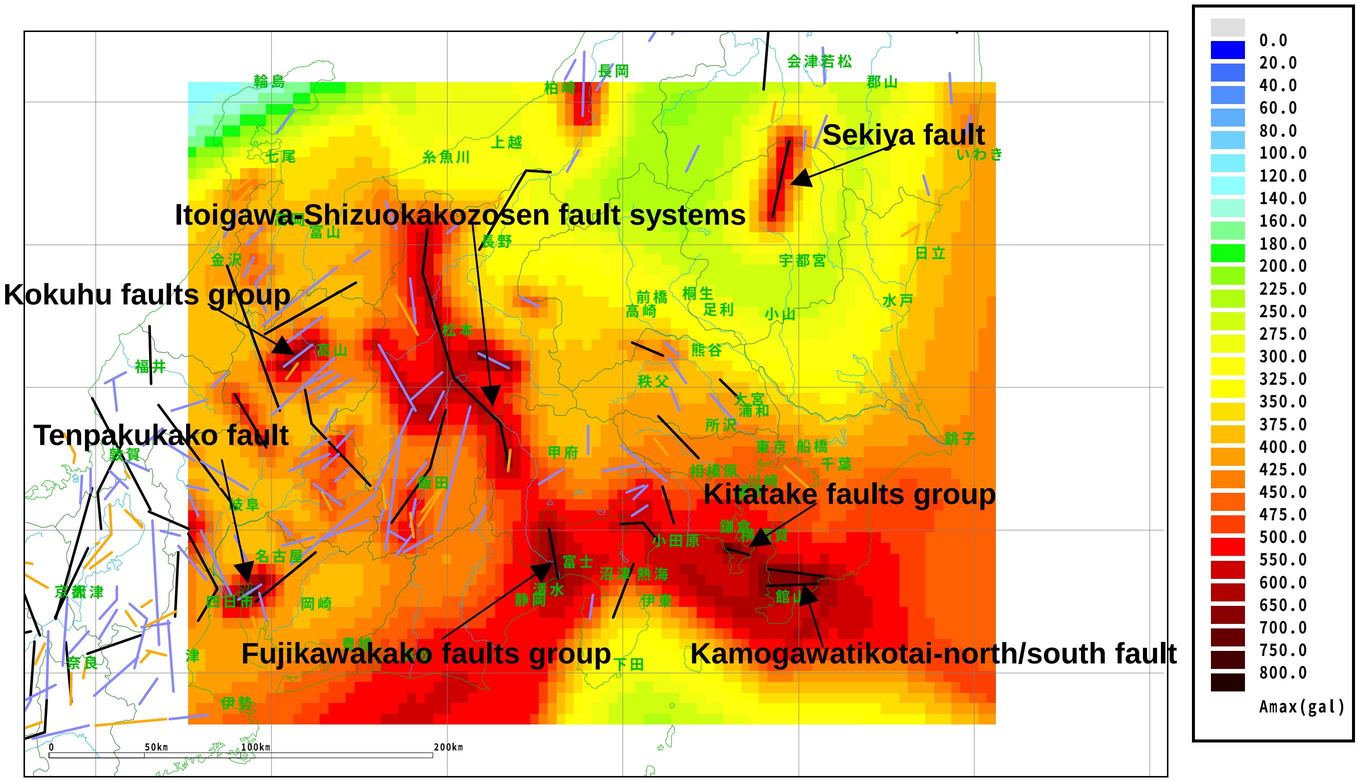


Fig.12 Seismic Hazard Map Based on Inter-plate Earthquakes
(PGA with 39.4% Probability of Exceedance during 500 Years)



(a) PGA with 39.5% Probability of Exceedance during 50 Years



(b) PGA with 39.4% Probability of Exceedance during 500 Years

Fig.13 Seismic Hazard Map Based on Past Earthquake Records, Active Faults and Inter-plate Earthquakes