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PROCEDURE FOR MAKING PROBABILISTIC SEISMIC HAZARD MAP AND UNDERSTANDING OF THE EVALUATED HAZARD

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SUMMARY

Past earthquake records have been primarily used for producing probabilistic seismic hazard maps. In the hazard analyses earthquakes with various magnitudes are assumed to occur randomly in time and space based on past earthquake records. However, earthquakes with particular magnitudes and recurrence intervals occur repeatedly on active faults and subduction zones. In the present paper we discuss a procedure to evaluate seismic hazards based on past earthquake records, active faults and inter-plate earthquakes. Resultant seismic hazard map is shown for all Japan. Japan Meteorological Agency Seismic intensity records, which have been observed at various sites in Japan for long periods, are employed for understanding of the evaluated seismic hazard.

INTRODUCTION

Past earthquake records have been primarily used for producing probabilistic seismic hazard maps (e.g. Arakawa [1] and Cornell [2]). Those maps have been applied to form regional classification maps in seismic design codes for various civil infrastructures in Japan so that regional seismicity is incorporated into seismic design motions. Past earthquake records used for producing seismic hazard maps are based on instrumental observation and historical descriptions. Though these records date back as long as one thousand and hundreds years, they are still insufficient to evaluate seismic hazard due to active faults, because recurrence intervals of active faults are generally longer than thousands of years. Besides, earthquakes with various magnitudes are assumed to occur randomly in both time and space in the analysis based on past earthquake records, however earthquakes with particular magnitudes and recurrence intervals occur repeatedly on active faults and subduction zones. Considering insufficiency of past earthquake records and the events repeatedly occurring on active faults and subduction zones, active faults and inter-plate earthquakes should be taken into consideration in seismic hazard analysis separately from past earthquake records. In the present paper we discuss a procedure to evaluate seismic hazards based on past earthquake records, active faults and inter-plate earthquakes (Nakao et al.[3]). Resultant seismic hazard map is shown for all Japan.

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In Japan seismic intensities have been recorded at various sites for long periods by Japan Meteorological Agency. We employ the seismic intensity records to compute observational seismic hazard. Note that almost all the seismic intensity records are attributed to the earthquakes that are assumed to occur randomly in time and space in the present procedure. Therefore, the seismic hazard based on past earthquake records is compared with the observational hazard in order to understand the evaluated hazard. Through the comparison, it is recognized that regional differences of the evaluated hazard roughly agree with those of the observational hazard. In the present procedure characteristics of the earthquakes that occur repeatedly on active faults and subduction zones are evaluated based on the latest seismological and geological researches, and they are reflected in hazard evaluation. The seismic hazard based on past earthquake records is complemented by the hazard based on active faults and inter-plate earthquakes.

PROCEDURE FOR MAKING PROBABILISTIC SEISMIC HAZARD MAP

Seismic Hazard Based On Past Earthquake Records

Earthquake Catalogs

Earthquake catalogs adopted in the present study are as follows:

-Usami Catalog [4] for 416-1884
-Utsu Catalog [5] for 1885-1925
-Japan Meteorological Agency (JMA) Catalog [6] for 1/1926- 7/1996

Figs.1(a) and (b) show cumulative numbers of earthquake records against time for events with Mj<6.0 and Mj≥6.0 (Mj is Japan Meteorological Agency Magnitude), 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

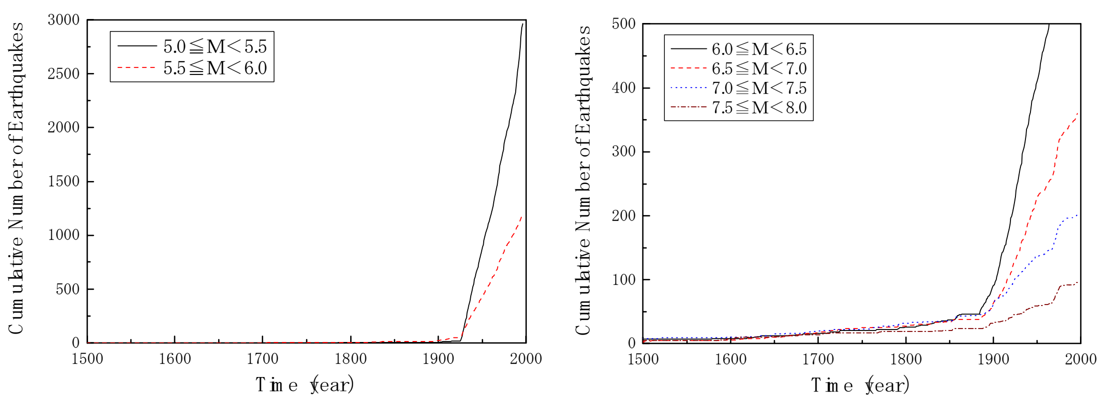


Fig.1 (a) Mj<6.0 **(b) Mj≥6.0**

Fig.1 Cumulative Number of Earthquake Records

Fig.2 shows the epicenters of past earthquakes included in the catalogs used for analysis. Note that we exclude records of the earthquakes attributed to active faults and the inter-plate earthquakes from the catalogs so that these earthquakes would not be doubly considered in hazard evaluations based on past earthquake records. The excluded earthquakes are considered in analysis based on active faults and inter-plate earthquakes separately from past earthquake records.

Based on seismotectonics around Japan after Hagiwara [7], we develop background zones in which uniform seismicity is assumed individually. The background zones are shown in fig.3. The largest magnitude of past earthquakes in each background zone is adopted as the maximum magnitude. The earthquake records used for assuming maximum magnitudes are included in the three catalogs (after Usami [4], Utsu [5] and JMA [6]). If magnitude of earthquake attributed to active fault or that of inter-plate earthquake is adopted as maximum magnitude, we adopt the largest one of the other events as maximum magnitude [8]. Maximum magnitude in each background zone is shown in Table 1. We do not employ magnitudes of earthquakes which occur repeatedly on active faults and subduction zones as maximum magnitudes because these earthquakes are considered in analysis based on active faults and inter-plate earthquakes separately from past earthquake records.

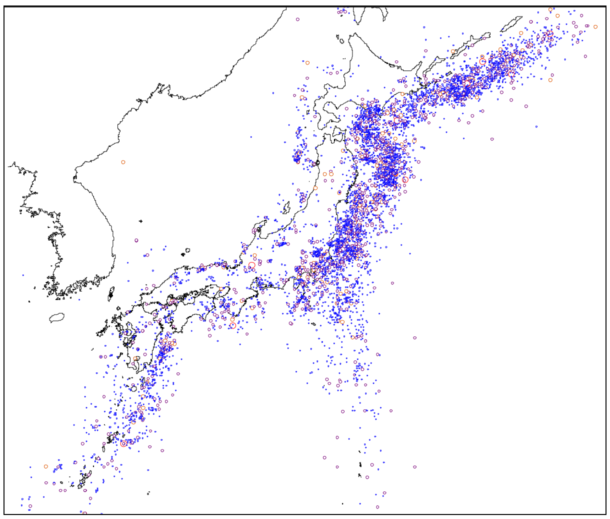


Fig. 2 Epicenters of Past Earthquakes

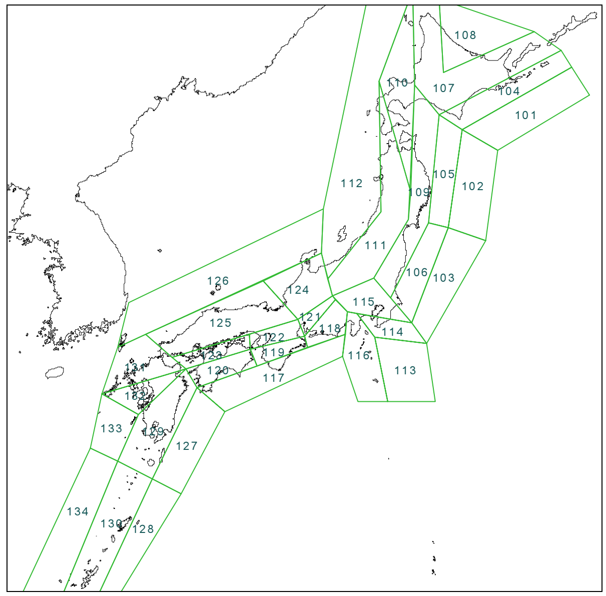


Fig.3 Background Zones

Table1 Earthquake Occurrence Modeling for Each Background Zone

Background Zone	Number of events	Minimum Magnitude	Maximum Magnitude	Upper and Lower layers of background zone				Upper layer of background zone (0 to 30 (km) forcal depth)		Lower layer of background zone (30 to 100 (km) forcal depth)	
				a value	b value	Average focal depth(Km)	Mean numbers of events per year (numbers/year)	Average focal depth(Km)	Mean number of events per year (number/year)	Average focal depth(Km)	Mean number of events per year (number/year)
101	527	5.0	8.1	4.76	0.84	36.7	3.62	14.5	1.64	55.1	1.98
102	771	5.0	8.5	4.62	0.77	24.4	5.82	10.0	3.82	53.6	2.00
103	272	5.0	8.0	4.37	0.80	33.1	2.34	13.7	1.18	52.8	1.16
104	411	5.0	7.8	5.06	0.90	48.6	3.68	14.6	0.85	58.8	2.83
105	432	5.0	8.5	5.02	0.88	37.5	4.34	17.2	1.85	52.6	2.49
106	628	5.0	8.0	4.58	0.79	33.7	4.50	12.1	1.98	50.6	2.52
107	83	5.0	7.3	4.41	0.89	49.8	0.92	14.7	0.34	70.6	0.58
108	3	5.0	7.3	1.36	0.56	20.0	0.04	10.0	0.02	40.0	0.01
109	292	5.0	7.5	5.39	0.97	52.6	3.34	12.1	0.70	63.3	2.64
110	18	5.0	7.3	5.05	1.13	16.7	0.26	10.0	0.22	66.7	0.04
111	73	5.0	7.6	4.74	0.96	7.0	0.88	10.0	0.86	90.0	0.02
112	165	5.0	7.8	6.37	1.14	19.7	4.66	12.6	3.62	44.4	1.05
113	174	5.0	7.4	5.47	1.02	42.4	2.33	13.6	0.90	60.4	1.43
114	72	5.0	7.5	3.04	0.64	49.0	0.65	12.3	0.20	65.2	0.45
115	212	5.0	7.3	4.93	0.92	46.1	2.14	12.9	0.59	59.0	1.54
116	157	5.0	7.3	5.11	0.97	18.9	1.86	10.5	1.48	51.6	0.38
117	71	5.0	7.8	3.66	0.76	18.6	0.69	10.3	0.56	55.5	0.13
118	37	5.0	8.0	4.45	0.97	14.5	0.41	10.0	0.35	41.0	0.07
119	39	5.0	8.0	4.02	0.88	32.4	0.40	10.0	0.20	56.0	0.19
120	41	5.0	8.0	6.57	1.36	25.7	0.58	10.0	0.33	46.3	0.26
121	18	5.0	7.5	4.95	1.13	12.8	0.21	10.0	0.18	43.3	0.04
122	13	5.0	7.8	4.84	1.10	16.3	0.23	10.0	0.19	52.5	0.04
123	20	5.0	7.8	2.62	0.67	42.7	0.19	15.0	0.07	61.1	0.11
124	49	5.0	7.3	4.50	0.94	7.0	0.65	10.0	0.63	37.0	0.01
125	107	5.0	7.4	4.71	0.93	8.4	1.12	10.0	1.09	41.3	0.03
126	17	5.0	7.3	5.03	1.11	22.3	0.29	16.9	0.22	40.0	0.07
127	232	5.0	7.8	5.08	0.92	31.1	3.05	11.3	1.59	52.6	1.46
128	127	5.0	8.0	4.03	0.77	46.9	1.52	13.7	0.45	61.1	1.06
129	70	5.0	8.0	4.64	0.96	29.0	0.69	10.0	0.43	66.7	0.26
130	87	5.0	8.0	4.85	0.98	30.3	0.84	10.0	0.46	58.9	0.38
131	10	5.0	7.3	3.22	0.82	18.8	0.13	10.0	0.11	100.0	0.01
132	34	5.0	7.3	4.82	1.03	5.9	0.47	10.0	0.47	-	0.00
133	17	5.0	7.3	4.15	0.98	20.7	0.18	10.0	0.14	57.5	0.04
134	33	5.0	7.3	3.19	0.72	28.9	0.37	10.0	0.23	67.6	0.13

It is possible that causative faults do not appear clearly on the ground surface even in the case of large-scale earthquakes such as The Western Tottori prefecture earthquake in 2000(Mj=7.3). The earthquakes attributed to concealed active faults are not considered in analysis based on active faults. Besides, it is possible that the large-scale earthquakes were not recorded in historical descriptions if they occurred on concealed active faults long years ago. These earthquakes are not considered also in analysis based on past earthquake records if magnitude of the events are larger than the adopted maximum magnitude in background zone. Therefore, Mj=7.3 of The Western Tottori prefecture earthquake is employed as lower limit of maximum magnitude in each background zone in order to consider concealed active faults. There are nine background zones that adopt the under limit as maximum magnitude. Mj=5 is employed as minimum magnitude in every background zone.

Gutenberg-Richter relationship given by eq.(1) is assumed to represent frequency distribution of earthquake magnitude for each background zone.

$$\log N_i\,[M>m] = a_i - b_i\, m \qquad (1)$$

where,

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

a_i, b_i: Coefficients for i-th background zone

Based on earthquake records within i-th background zone, a_i and b_i–values are determined by method of maximum likelihood as shown in Table 1. Mean earthquake occurrence rate per year and area in i-th background zone is computed by eq.(2).

$$\nu_i = \frac{(10^{a_i - b_i Mi_L} - 10^{a_i - b_i Mi_U})}{A_i} \qquad (2)$$

where,

A_i: Area of i-th background zone

Mi_L: Minimum magnitude of earthquakes considered in analysis. (Mj = 5.0)

Mi_U: Maximum magnitude in i-th background zone

Figs.4 (a) and (b) show epicenters with focal depths of 0 to 30 (km) and 30 to 100 (km), respectively. According to figs.4 it is evident that almost all events in north side of Japan and Japan Sea occur at the depth of 0 to 30(km). In order to consider the seismicity and ground motion intensity depending on focal depth we divide background zones into upper and lower layers. Upper layer of background zone is 30km thick surface part of the zone and lower layer of zone is 70km thick part underneath the upper layer. Earthquakes are assumed to occur in both layers in analysis. Mean earthquake occurrence rate per year and area in upper and lower layers are computed by eq. (3) and (4), respectively. Uniform earthquake occurrence rate per year and area is assumed in each layer.

$$\nu_i^{upper} = \nu_i \frac{N_i^{upper}}{N_i^{upper} + N_i^{lower}} \qquad (3)$$

$$\nu_i^{lower} = \nu_i \frac{N_i^{lower}}{N_i^{upper} + N_i^{lower}} \qquad (4)$$

where,

N_i^{upper} : Number of earthquake records in upper layer of i-th background zone

N_i^{lower} : Number of earthquake records in lower layer of i-th background zone

ν_i: Mean earthquake occurrence rate per year and area in i-th background zone

ν_i^{upper} : Mean earthquake occurrence rate per year and area in upper layer of i-th background zone

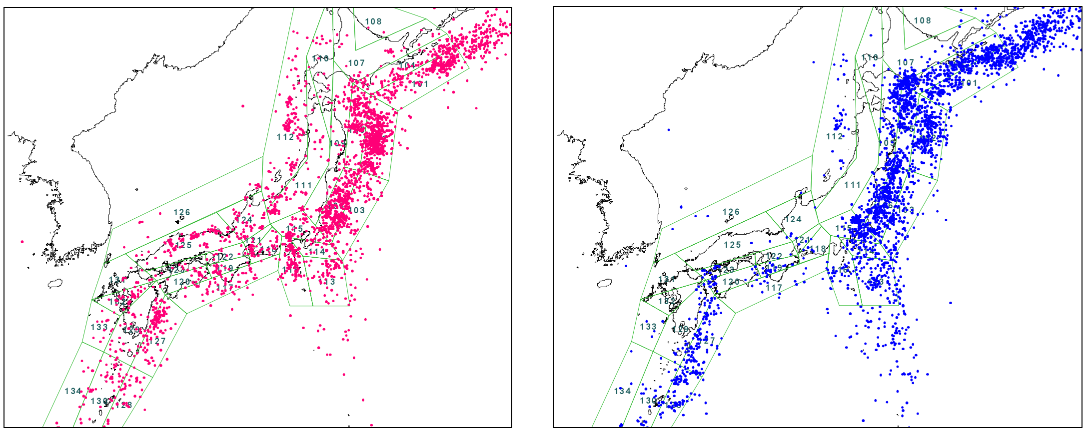
ν_i^{lower} : Mean earthquake occurrence rate per year and area in lower layer of i-th background zone

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

$$fi_M(m) = \frac{b_i \exp[-b_i(m - Mi_L)]}{1 - \exp[-b_i(Mi_U - Mi_L)]} \qquad (5)$$

where,

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



(a) 0≤h<30 (km) **(b) 30≤h<100 (km)**

Figs.4 Epicenters of Past Earthquakes with Different Focal Depth h

Ground Motion Attenuation Relation with Distance

In the present study peak ground acceleration (PGA) is estimated by attenuation relation after Annaka et al.[9], which is given by eq.(6).

$$\log X = 0.606M + 0.00459H - 2.136\log(R + 0.334e^{0.653M}) + 1.730 \qquad (6)$$

where,

X: Peak ground acceleration [gal]

M: Japan Meteorological Agency magnitude

H: Focal depth [km]

R: The shortest distance between site and fault plane [km]

PGA on the outcropped bedrock whose shear wave velocity is larger than 300 to 600m/sec is estimated by eq. (6). Although they use the shortest distance to a fault plane as a distance parameter, we substitute hypocentral distance for the shortest distance. Average depth of focuses in each layer of background zones is used as focal depth parameter in the attenuation relation. 10km is given to focal depth parameter as lower limit. 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

$$P x_i[X > x \mid m, r, h] = \int_X^{\infty} fx_i(X \mid m, r, h)dX \qquad (7)$$

where,

fx_i(X |m,r,h): Probability density function of PGA generated by an earthquake with magnitude m at a distance r and focal depth h.

m: Japan Meteorological Agency magnitude

r: The shortest distance between site and fault plane [km]

h: Focal depth [km]

Hazard Evaluation Based on Past Earthquake Records

Combining eqs.(3), (4) ,(5) and (7), probability that PGA X exceeds x during a period of T_D can be given by eq.(8).

$$P_h[X > x \mid T_D] = 1 - \exp(-\lambda T_D) \qquad (8)$$

$$\lambda = \int_A \int_{Mi_L}^{Mi_U} \left(\nu_i^{upper} fi_M(m) P x_i[X > x \mid m, r, H_i^{upper}] + \nu_i^{lower} fi_M(m) P x_i[X > x \mid m, r, H_i^{lower}] \right) dmds \qquad (9)$$

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 that PGA X exceeds x during a year

H_i^{upper} : Average depth of focuses in upper layer of i-th background zone

H_i^{lower} : Average depth of focuses in lower layer of i-th background zone

A: Area in which all the assumed earthquakes are considered in analysis

Seismic Hazard Based of Active Faults

Active Faults for Analysis

We employ the following two kinds of active faults for analysis. Active faults categorized in (2) are also assumed to generate independent earthquakes in the same way as the faults in (1). Fig.5 shows locations of seismogenic and active faults.

(1)Seismogenic faults after Matsuda[10]: 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[11])

Magnitudes and Occurrence rates

Matsuda [12] derived relationships among fault length, dislocation and earthquake magnitude as eqs. (10) and (11). Introducing an average slip rate of fault, we can evaluate mean recurrence interval by eq. (12). When a wide range of average slip rate is given for an active fault, we use the middle value of the range; i.e. when 1 to 10[mm/year], 0.1 to 1[mm/year] and 0.01 to 0.1[mm/year] are given as ranges, we use 5[mm/year], 0.5[mm/year] and 0.05[mm/year] as an average slip rate, respectively. When a number of average slip rates are obtained along fault line, we use the largest rate of them.

$$M_j = (\log(L_j) + 2.9) / 0.6 \qquad (10)$$

$$M_j = (\log(D_j) + 4.0) / 0.6 \qquad (11)$$

$\log(T_{Rj}) = \log(L_j / \nu_j)+1.9$ (12)

where,

M_j: Magnitude

L_j: Fault length [km]

D_j: Dislocation of fault rupture [m]

T_{Rj}: Mean recurrence interval [year]

ν_j: Average slip rate [m/year]

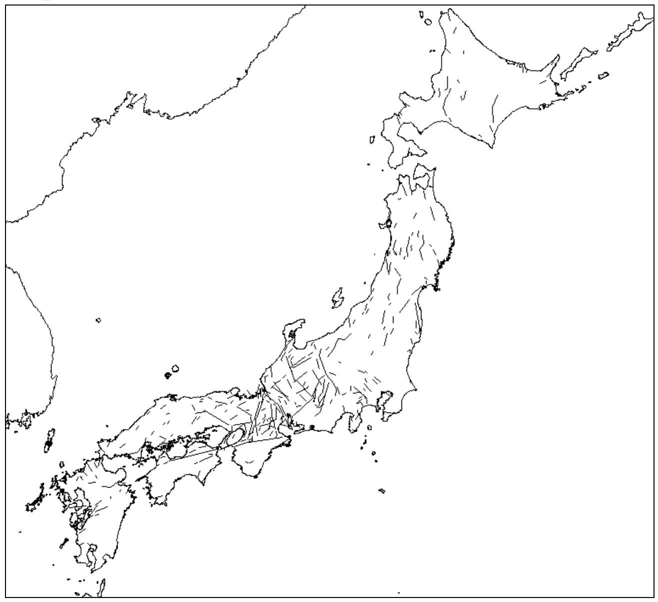


Fig.5 Seismogenic Faults and Active Faults

The Headquarters for Earthquake Research Promotion [13] was installed by Prime Minister's office after the 1995 Kobe Earthquake. The Headquarters is promoting survey at 98 major active faults. Ministry of Education, Culture, Sports, Science and Technology [14] and Geological Survey of Japan[15] also conduct surveys on active faults. We incorporate newly obtained information by those surveys into analysis. When the occurrence time of the latest event is known, we assume a time-dependent stochastic process model for earthquake occurrence, which is given by eq.(13). We use a Brownian passage time distribution for this model [13]. When the occurrence time of the latest event is unknown, we employ stationary Poisson process for earthquake occurrence as shown by eq.(14)[13].

$$P_j[T_D]=\frac{F_j(t_{0j}+T_D)-F_j(t_{0j})}{1-F_j(t_{0j})} \quad (13)$$

$$P_j[T_D]=1-e^{-\frac{T_D}{T_{Rj}}} \quad (14)$$

where,

T_D: Time interval to calculate probability of earthquake occurrence [year]

T_{Rj}: Mean recurrence interval [year]

$F_j(t)$: Brownian Passage Time distribution function of recurrence interval

t_{0j}: Elapsed time from the latest event [year]

$P_j[T_D]$: Probability of earthquake occurrence

Ground Motion Attenuation Relation with Distance

We employ ground motion attenuation relation after Annaka et al.[9] for analysis based on active faults the same as the case of past earthquake records. The shortest distance to a fault plane is used as distance parameter. In eq.(6) focal depth is defined as depth of central point on the fault plane. Assuming all the fault widths to be 13km and all the fault dip to be 90˚, we adopt 6.5km as focal depth. The assumption of fault width is based on the followings. As for more than 70% of active faults earthquake magnitudes are estimated to be larger than or equal to Mj6.8. According to the relationship between magnitudes and fault widths after Takemura [16], fault widths of earthquakes with Mj 6.8 saturate at 13[km].

In the same manner as eq.(7), probability that PGA X exceeds a specific level x due to an earthquake generated by j-th active fault is written as eq. (15).

$$P x_j[X > x \mid M_j, r, 6.5] = \int_X^{\infty} f x_j(X \mid M_j, r, 6.5) dX \qquad (15)$$

Hazard Evaluation Based on Active Faults

Using eqs. (13)-(15), we can calculate probability that PGA X exceeds x during T_D years due to j-th active fault by eq.(16). Probability that PGA X exceeds x during T_D years due to all active faults is computed by eq.(17).

$$P_{f\,j}[X > x, T_D] = P_j[T_D] P x_j[X > x \mid M_j, r] \qquad (16)$$

$$P_f[X > x, T_D] = 1 - \prod_j \left\{1 - P_{f\,j}[X > x, T_D]\right\} \qquad (17)$$

Seismic Hazard Based on Inter-plate Earthquakes

Inter-Plate Earthquakes for Analysis

Large-scale earthquakes that occur repeatedly in subduction zones are considered as inter-plate earthquakes. Inter-plate earthquakes introduced in analysis are shown in fig.6 and table2. In the followings we discuss fault planes, magnitudes, and recurrence intervals established for each inter-plate earthquake.

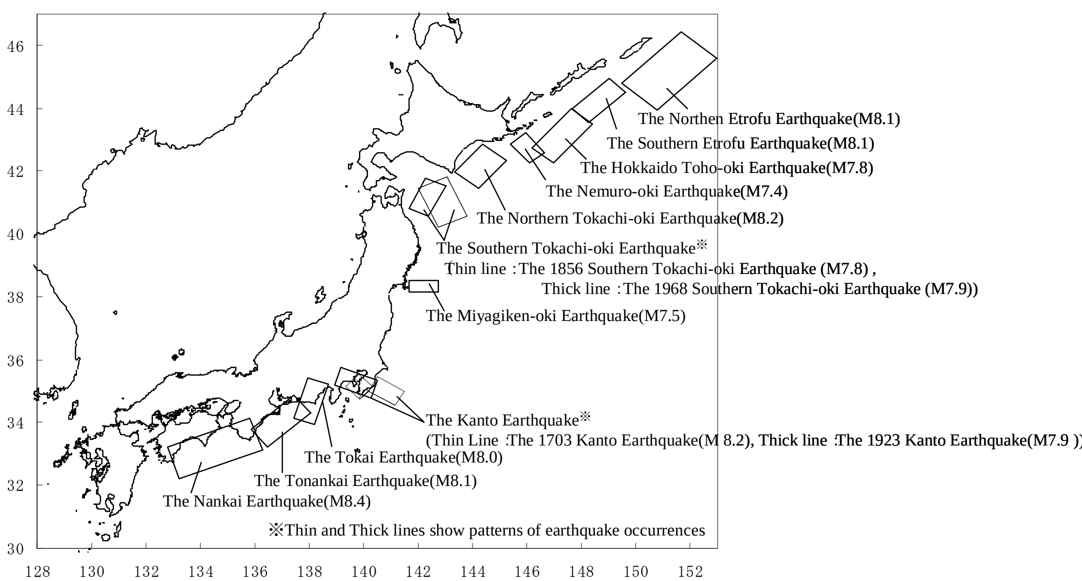


Fig.6 Inter-plate Earthquakes

Table 2 Inter-plate Earthquakes Considered in Analysis

Inter-plate Earthquakes	Magnitude	Mean Recurrence Interval [year]	The Latest Earthquake Occurrence Time	α for BPT Distribution Model
The Nankai Earthquake	M8.4	90.1	12/21/1946	0.20
The Tonankai Earthquake	M8.1	86.4	12/7/1944	0.18
The Tokai Earthquake	M8.0	118.8	12/23/1854	0.24
The Kanto Earthquake	M7.9 or M8.2	219.8	9/1/1923	0.24
The Miyagiken-oki Earthquake	M7.5	37.1	6/12/1978	0.18
The Southern Tokachi-oki Earthquake	M7.8 or M7.9	57.0	6/30/1962	0.18
The Northern Tokachi-oki Earthquake	M8.2			
The Nemuro-oki Earthquake	M7.4			
The Hokkaido Toho-oki Earthquake	M7.8			
The Southern Etorofu Earthquake	M8.1			
The Northern Etorofu Earthquake	M8.1			

Fault Planes, Magnitudes, Recurrence Intervals, The Latest Event Time

-Earthquakes in the Pacific Ocean off the Coast of Hokkaido and North Tohoku Region areas

The Headquarters for Earthquake Research Promotion [17] suggests that inter-plate earthquakes in the Pacific Ocean off the coast of Hokkaido and North Tohoku Region areas occur within a relatively short period of time, and their source regions do not overlap as shown in fig.7. These earthquakes can be explained in the following way. Strain accumulates over a period of several decades to 100 years in the area adjoining the Chishima (Kuril) Trench due to the subducting Pacific Plate. After this strain has approached its limit, it is released by a series of inter-plate earthquakes. As a result, a series of large-scale earthquakes occurs along the trench in a short time with no overlapping of focal regions. Past earthquakes in this region are categorized into different sets of event series by Utsu[18] as shown in fig.8. We employ time interval of median years in last two sets of event series as a mean recurrence interval in common for inter-plate earthquakes along the Chishima Trench. The median year of the latest set of event series is employed as the latest event time in common for all the inter-plate earthquakes. We suppose source locations and magnitudes of earthquakes in this region based on past events [22]. Note that we suppose two patterns with same probability to occur as for magnitudes and source locations of the Southern Tokachi-oki Earthquake as shown in fig.6 and table2.

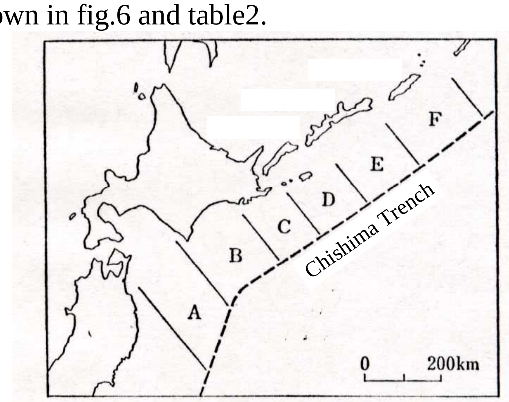


Fig.7 Earthquakes in the Pacific Ocean off the Coast of Hokkaido and North Tohoku Region Areas

A	B	C	D	E	F	Time Interval	
1763 M8		unclear			1780 M8	17 years	Time Interval of a Series of Earthquake Occurrences
						59 years	
1856 M8	(1839 M7.5)		— 1843 M8+ →	unclear		17 years	Time Interval of a Series of Earthquake Occurrences
						37 years	
		← 1894 M7.9	1893 M7.75	(1918 M7.7)	* 1918 M8.0	25 years	Time Interval of a Series of Earthquake Occurrences
						34 years	
1968 M7.9	1952 M8.2	(1973 M7.4)	1969 M7.8	1958 M8.1	1963 M8.1	21 years	Time Interval of a Series of Earthquake Occurrences

Mean Recurrence Interval 57(years)

Source Place of the 1896 Sanriku-oki Earthquake overlapped.
* The 1918 Earthquake may have occurred in F zone.

Fig.8 Past Earthquakes in the Pacific Ocean off the Coast of Hokkaido and North Tohoku Region Areas

-The Miyagi-oki Earthquake, the Tonankai Earthquake and the Nankai Earthquake
We suppose source locations, magnitudes, mean recurrence intervals, and the latest event time according to The Headquarters for Earthquake Research Promotion [13].

-The Kanto Earthquake
Mean recurrence interval of the Kanto earthquake is evaluated as 220 years based on past Kanto earthquakes in 1703 and 1923. The year 1923 of the last Kanto earthquake is employed as the latest event time. Similar to the case of the South Tokachi-oki earthquake, we suppose two patterns with same probability to occur as for magnitudes and source locations as shown in fig.6 ([19] and [20]).

-The Tokai Earthquake
We suppose source location and magnitude for the Tokai Earthquake according to Central Disaster Prevention Council[21]. Mean recurrence interval and the latest event time are supposed as shown in table2 based on series of events in Z region shown in fig.9 and table 4.

For evaluating event rates of the inter-plate earthquake Brownian Passage Time distribution function for recurrence interval is employed [13].

Ground Motion Attenuation Relation
Eq.(6) is used for ground motion estimation from inter-plate earthquakes. The shortest distance to fault planes is employed as distance parameter. Depth of the center point on a fault plane is used as focal depth in the attenuation relation. For incorporating the scatter of ground motion estimated by attenuation relation into analysis, ±2σ variation around mean value is considered, where σ represents a standard variation of attenuation equation.

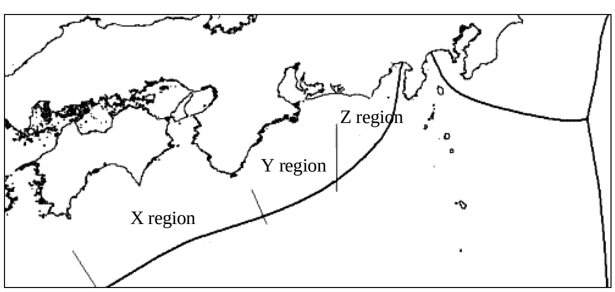


Fig.9 Source Regions for The Nankai Earthquake, The Tonankai Earthquake, and The Tokai Earthquake

Table 4 Source Regions

Event Time	Earthquake	X Region	Y Region	Z Region
9/20/1498	The Meio Tokai Earthquake		**	*
2/3/1605	The Keicho Earthquake		**	*
10/28/1707	The Hoei Earthquake	**	**	*~**
12/23/1854	The Ansei Tokai Earthquake		**	**
12/24/1854	The Ansei Nankai Earthquake	**		
12/7/1944	The Showa Tonankai Earthquake		**	
12/21/1946	The Showa Nankai Earthquake	**		

(**: Source zone overlaps almost all the region, *: Source zone overlaps part of the region)

Hazard Evaluation Based on Inter-plate Earthquakes

Recurrence intervals of inter-plate earthquakes are shorter than those of active faults. Therefore, we consider three times occurrences for each inter-plate earthquake in hazard analysis [22]. Probability that PGA X exceeds x during T_D years due to i-th inter-plate earthquake is computed by eq.(18). Probability that PGA X exceeds x during T_D years due to all inter-plate earthquakes is evaluated by eq.(20).

$$P_{p_i}[X > x, T_D] = 1 - \prod_{n}^{3} (1 - P_i[T_D, n] Px_i[X > x \mid m_i, r, h]) \qquad (18)$$

$$P x_i[X > x \mid M_i, r] = \int_{X}^{\infty} fx_i(X \mid M_i, r, h) dX \qquad (19)$$

$$P_p[X > x, T_D] = 1 - \prod_{i}^{N} (1 - P_{p_i}[X > x, T_D]) \qquad (20)$$

where,

$P_i[T_D, n]$: Probability that i-th inter-plate earthquake occurs once more following to n-1 times occurrences of it during T_D years

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

$P xi[X > x \mid M_i, r, h]$: Probability that PGA X exceeds a specific level x due to an event of magnitude M_i

$P_P[X > x, T_D]$: Probability that PGA X exceeds x during T_D years due to all inter-plate earthquakes

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.(21) on the assumption that these three earthquake sources are independent each other.

$$P[X > x, T_D] = 1 - (1 - P_h[X > x \mid T_D])(1 - P_f[X > x, T_D])(1 - P_p[X > x, T_D]) \qquad (21)$$

where,

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

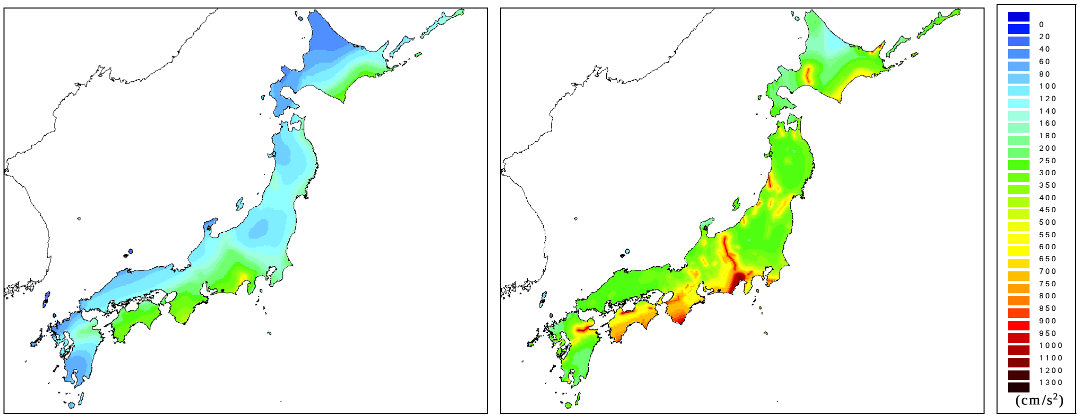
$P_f[X>x, T_D]$: Probability that ground motion X from active faults exceeds x during T_D years

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

Resultant Seismic Hazard Map

Figs.10(a) and (b) present seismic hazard maps in which past earthquakes, active faults and inter-plate earthquakes are incorporated. PGA with 63% and 5% probability of exceedance during 100 years from the year 2003 are shown in figs.10(a) and (b), respectively.

According to the numerical results in figs.10, the active faults with high event rates and inter-plate earthquakes affect seismic hazards nearby. Strong ground motions are estimated widely around areas with high dense distributions of active faults.



(a) 63% probability of exceedance **(b) 5% probability of exceedance**

Fig.10 PGA with 63% and 5% Probabilities of Exceedance in 100 Years from The Year 2003

UNDERSTANDING OF THE EVALUATED SEISMIC HAZARD

Evaluated Seismic Hazard According to the Present Procedure

According to the present procedure seismic hazards are evaluated at the sites, where Japan Meteorological Agency (JMA) has announced the JMA seismic intensities for longer than 50 years. The evaluated seismic hazards are compared with observational seismic hazards that are computed from the announced seismic intensity records. The seismic intensity, which provides a measure of the strength of seismic motion, is divided into 10 scales. The relationship between seismic intensity on JMA scale and Modified Mercalli intensity is shown in fig.11 for reference.

JMA Seismic Intensity	0	1	2	3	4	5 Lower	5 Upper	6 Lower	6 Upper	7
JMA Measured Seismic Intensity	<0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	6.5<
Modified Mercalli Seismic Intensity	1	2	3	4 5	6 7	8		9		10 11 12

Fig.11 JMA Seismic Intensity and MM Intensity [23]

Note that we evaluate seismic hazards based on only past earthquake records for the comparison with the observational ones because almost all the observed seismic intensity records are from the earthquakes that are assumed to occur randomly in time and space in the present procedure. In the hazard evaluation probability that JMA seismic intensity x is larger than or equal to intensity 4 during a year is computed.

In hazard analysis Seismic intensities are estimated by attenuation relation after Shabestari, K. et al.[24], which is given by eq.(22). As shown in fig.11 seismic intensity is divided into 10 scales based on measured seismic intensity, which is continuous value measured by seismic intensity meters. The measured seismic intensity is estimated by eq.(22) and fig.11 yields seismic intensity based on the estimation. We determine station coefficient in eq.(22) so that the sum of squares of the residual that is defined as differences between estimated seismic intensities and observed ones at each site is minimized. For incorporating the scatter of measured seismic intensity estimated by attenuation relation into analysis, $\pm 2\sigma$ variation around mean value is considered, where σ represents a standard variation of attenuation equation.

$$I = -0.087 + 1.053M - 0.00256r - 1.89\log r + 0.00496h + c \qquad (22)$$

where,

I : Measured seismic intensity

M: Japan Meteorological Agency magnitude
r: The closest distance to fault rupture
h: Source depth
c: Station coefficient

Observational Seismic Hazard

All the seismic intensity records due to active faults and inter-plate earthquakes, which are considered separately from background zones in the present procedure, are excluded for observational computation of seismic hazard. As shown in fig.12 the sites for the hazard computation are chosen so that they cover almost all Japan. At the sites seismic intensity has been announced for no shorter than 50 years. Based on the long-term seismic intensity records we compute probability that JMA seismic intensity x is larger than or equal to intensity 4 during a year.

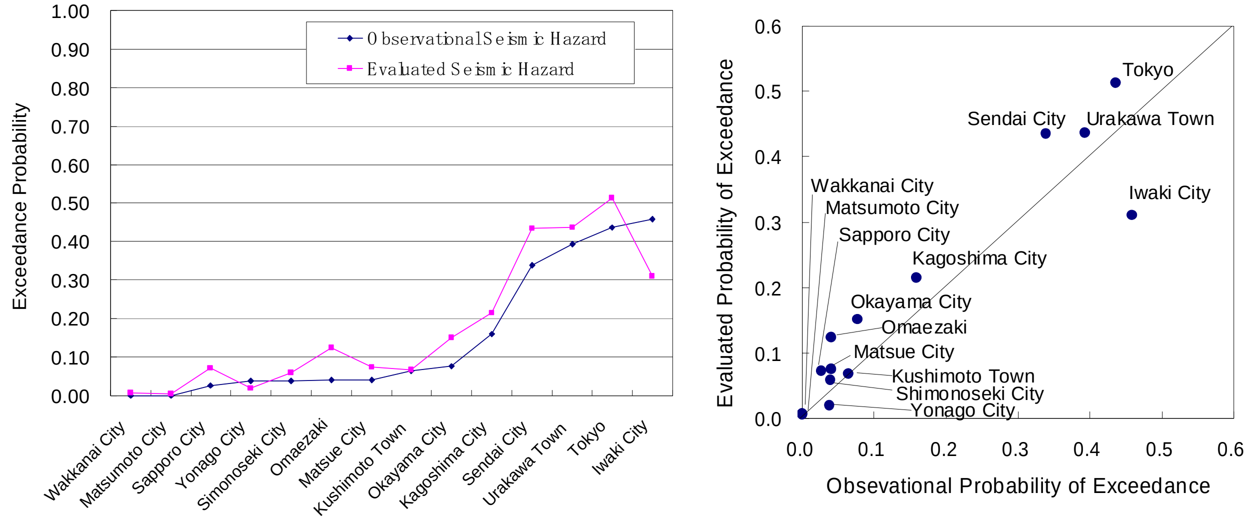
Fig.12 Sites Chosen for Hazard Evaluation

Note that JMA Seismic intensity has been measured automatically with seismic intensity meters since 1996, while former JMA seismic intensity had been determined from human response or observation of damage. However, it is shown that former seismic intensity agrees well with instrumentally measured one [25]. Therefore, we employ seismic intensity records before 1996 in addition to instrumentally measured records for the computation of observational seismic hazard.

Understanding of Evaluated Seismic Hazard

Seismic hazards evaluated at various sites are compared with the observational ones in figs.11. Because maximum magnitudes assumed for background zones in the hazard analysis are larger than the magnitudes of earthquakes that occurred actually in limited periods of time, probabilities of exceedance tend to be evaluated conservatively. According to figs.11, regional differences of exceedance probabilities obtained from the hazard analysis based on past earthquake records agree roughly with the observationally computed ones.

In the present procedure recurrence intervals, source locations, and magnitudes of the earthquakes that occur repeatedly on active faults and subduction zones are evaluated based on the latest researches on active faults and inter-plate earthquakes, and those characteristics of earthquakes are reflected in hazard evaluation. The seismic hazard based on past earthquake records, whose regional differences agree with the observations, is complemented by the hazard based on active faults and inter-plate earthquakes.



(a) Sorted by Observational Probability of Exceedance **(b) Relationship Between Evaluated Probability and Observational One**

Fig.11 Probability that seismic intensity x is larger than or equal to Intensity 4 During a Year

CONCLUSION

The following conclusions are deduced from the present study.

1) We incorporate three kinds of earthquakes, i.e., earthquakes that occur randomly in both time and space within background zones, earthquakes from active faults and inter-plate earthquakes, into seismic hazard analysis. Assuming that each kind of earthquake occurs independently, a joint seismic hazard due to three sources is estimated. Results are shown for PGA with 63% and 5% probabilities of exceedance during 100 years from the year 2003.
2) According to the results active faults with high event rates and inter-plate earthquakes affect seismic hazards nearby. Besides, strong ground motions are estimated widely around areas with high dense distributions of active faults.
3) JMA seismic intensity records, which have been observed for long periods of time at various sites in Japan, are employed for understanding of the evaluated seismic hazard. It is recognized that the seismic hazard based on past earthquake records tend to be evaluated conservatively, and regional differences of the seismic hazard agree roughly with the observational ones. In the present procedure the seismic hazard based on past earthquake records is complemented by the hazard based on active faults and inter-plate earthquakes.

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REFERENCES

1. Arakawa, T. (1983). “Probabilistic Procedure in Selecting Input Motions for Dynamic Response Analysis”, Technical Memorandum, No.1992, Public Works Research Institute, Ministry of Construction (in Japanese)

2. Cornell, C. A.(1968). “Engineering Seismic Risk Analysis”, Bull. Seism. Soc. Am. Vol.58
3. Nakao, Y., Kusakabe, T., Murakoshi, J., and Tamura, K. (2003). “ Procedure for Producing Probabilistic Seismic Hazard Maps”, Research Report of National Institute for Land and Infrastructure Management, No.16 (in Japanese)
4. Usami, T. (1996). “ Materials for Comprehensive List of Destructive Earthquake in Japan”, University of Tokyo Press (in Japanese)
5. Utsu, T. (1987). “ Encyclopedia of Earthquake ”, Asakura Publishing Co., Ltd. (in Japanese)
6. Japan Weather Association (1995), ”Catalog of Major Earthquakes Which Occurred in and around Japan
7. Hagiwara, T. (1991),” Earthquake Engineering and Seismotectonics”, Kajima Institute Publishing Co., Ltd. (in Japanese)
8. Property and Casualty Insurance Rating Organization of Japan(2000). “Study on Seismic Hazard Considering Active Faults and Historical Earthquakes”, Research Report for Earthquake Insurance No.47 (in Japanese)
9. Annaka, T. et al (1997). “ Proposal of Attenuation Equation of Peak Ground Motion and Response Spectrum Based on JMA-87 type Accelerogram”, Proc. of 24th JSCE Symposium on Earthquake Engineering (in Japanese)
10. Matsuda, T. et al (2000) “ Distribution of M≧5 shallow earthquakes and active faults on Japanese islands”, Active Fault Research, Vol. 20(in Japanese)
11. Research Group for Active Faults (1991), ” Active Faults in Japan, Sheet Maps and Inventories, Revised Edition”, The Univ. of Tokyo Press (in Japanese)
12. Matsuda, T. (1975) “ Magnitude and Recurrence Interval of Earthquakes from a Fault, Jisin Journal, Seism. Soc. Japan, Vol. 28
13. Headquarters for Earthquake Research Promotion, “Long Term Evaluation”, http://www.jishin.go.jp/main/index.html
14. Science and Technology Agency (1995-1999), Proceedings of Active Faults Research (in Japanese) Ministry of Education, Culture, Sports, Science and Technology (2001), Proceedings of Active Faults Research (in Japanese)
15. Geological Survey of Japan (1998-1999), Interim Reports on Active Fault and Paleoearthquake Researches in the 1998 and 1999 Fiscal Year
16. Takemura, M. (1990) “ Magnitude-seismic moment relations for the shallow earthquakes in and around Japan”, Journal of the Seismological Society of Japan, Vol.43
17. Headquarters for Earthquake Research Promotion (2001), Seismic activity in Japan -- regional perspectives on the characteristics of destructive earthquakes
18. Utsu, T. (1984).,“ Seismology”, Kyoritsu Shuppan Co., Ltd.
19. Sato, R. et al. (1989),“ Source Parameters for Earthquakes in Japan”, Kajima Publishing Co., Ltd.
20. Wald, D. J. and Somerville, P. G. : Variable Slip Rupture Model of the Great 1923 Kanto Earthquake, Bull. Seism. Soc. Am. Vol.85, 1995
21. Central Disaster Prevention Council (2001), “ Paper in 7th Technical Committee on The Tokai Earthquake”
22. Ishikawa, H. (2001), “ Producing Seismic Hazard Map and Problems”, 2nd Workshop on Earthquake Research and Earthquake Disaster Prevention Engineering (in Japanese)
23. Japan Meteorological Agency (1996), ”Understanding of Seismic Intensity”, Gyosei Co., Ltd.
24. Shabestari, K. and Yamazaki, F.(1997): “Attenuation of JMA Intensity Based on JMA-87-type Accelerometer Records”, Proceedings of the 2nd Symposium on the disaster by urban area earthquakes
25. Midorikawa, S. et al(1999).,”Correlation of New J.M.A. Instrumental Seismic Intensity with Former J.M.A. Seismic Intensity and Ground Motion Parameters”, Journal of Institute of Social Safety Science, Vol.1