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COMPREHENSIVE FORECAST OF DESTRUCTIVENESS FOR HUGE EARTHQUAKES IN SUBDUCTION ZONE OF JAPAN

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ABSTRACT

This paper presents the estimation of extensive distributions of seismic intensity in Tokai region for the huge scenario earthquakes which occur along the Nankai Trough. In the analysis, the fault parameters of the scenario earthquakes of Tokai, Tounankai, and their coupled earthquakes were determined referring to those estimated by the National Disaster Prevention Council, Japan. The two techniques developed by the author were used; one is the simulation technique, EMPR, for non-stationary strong motion time histories on the upper surface of so-called engineering basement rock, and the other is the seismic response analysis for the multi-layered surface ground, FDEL, which incorporates the effect of frequency dependent equivalent strain characteristics on the shear rigidity and damping of soil. The soil structure models were used to incorporate the effect of surface geology on ground motion. They were assigned to approximately 180,000 points equally distributed in the region.

The typical characteristics on the seismic intensity distributions for the three scenario earthquakes were derived, and the areas exposed to severe seismic intensities were compared in the three scenario earthquakes and those during the 1995 Hyogoken Nambu Earthquake. Another measure, PEX(population exposure to seismic intensity) proposed by Nojima *et al.*(2004), was also examined for these earthquakes demonstrating the destructiveness of the earthquakes against the regional society as a whole.

Key words: Scenario Earthquakes, Strong motion prediction, Database for soil structure models, Extensive distribution map of seismic intensity, Tokai Earthquake

1. INTRODUCTION

After the disastrous experience of the 1995 Hyogoken Nambu Earthquake, most of the local governments in Japan have surveyed the detailed seismic disaster aspects toward the active faults in and around the area. Even the fault size is relatively small and those recurrence intervals are generally long, such as the order of several thousand years, the prefectural government have exerted an effort to identify the destructiveness of earthquakes due to the active faults in and around the area.

On the other hand, the high probability of earthquake occurrence has been estimated for the huge earthquakes in the subduction zone along the Japan Trench. The characteristic of earthquake disaster of these huge subduction earthquakes would be as follows : The seismic disaster is spread over in vast area, and a large number of people would be injured or killed. Consequently, it would take considerably long time for rescue and restoration.

Confronting these earthquake disasters, we need the seismic intensity map as the minimum required information for the effective disaster-prevention measures. The seismic intensity map for a scenario earthquake is generally obtained on the basis of the prediction technique for ground motion as well as the detailed fault parameters and local ground condition over the area.

This paper presents the estimation of extensive distributions of seismic intensity in Tokai region for the huge scenario earthquakes which occur along the Nankai Trough. The two indices which represent the seismic destructiveness are discussed for the three huge scenario earthquakes as well as the 1995 Hyogoken-Nambu Earthquake.

2. SEISMICITY OF TOKAI REGION AND SCENARIO EARTHQUAKES IN SUBDUCTION ZONE

2.1 Seismicity of Tokai Region

In the region, off-shore of the middle of Honshu and Shikoku Island, the huge earthquakes occurred frequently. Fig.1 shows the occurrence record of huge earthquakes along Nankai Trough in the last 3,000 years (Ando,1999). Fig.1 includes the occurrence record which was clearly specified in the historical documents in last 500 years, as well as the record which was identified by the mudflow sediments, tsunami sediments, and archeological sites. According to the occurrence record in last 500 years the return period of the huge earthquakes in this region was estimated as 90 to 150 years.

It is quite a short return period compared with that of inland active faults, since the return period of the active faults are generally in the order of a thousand or several thousands years. In the region, E, shown in Fig.1, the earthquake has not occurred since the last event of 1854, and the National Disaster Prevention Council (NDP,2001) has reported that the occurrence probability in 30 years is 90 % in this region. Also, the council reported the probability of 60 % in the region C and D where the Tounankai Eq. occurred in 1944.

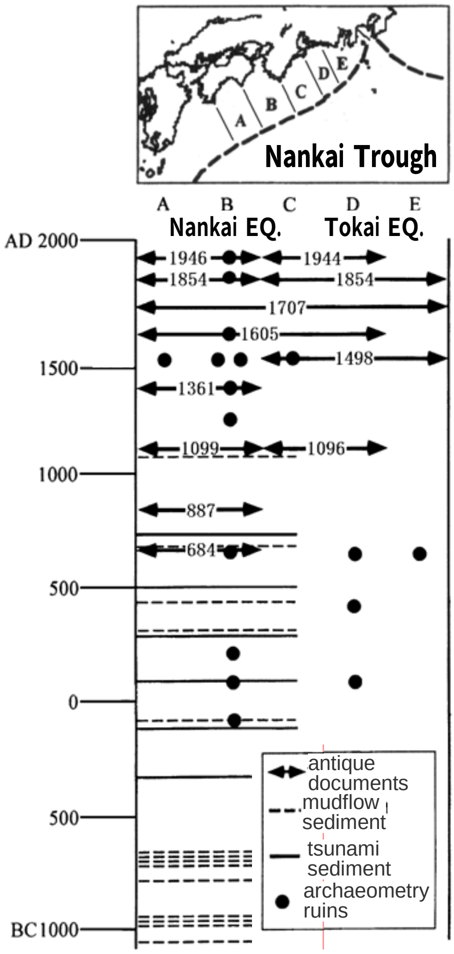

Fig.1 Occurrence Record of Huge Earthquakes along Nankai Trough in last 3,000 years (Ando, 1999).

2.2 Scenario Earthquakes in Subduction Zone

The National Disaster Prevention Council (2001) estimated the fault model for Tokai Eq. in 1979 shown by a rectangle model in Fig.2, and the region, where the urgent preparation against the seismic disaster is requested, has been designated. In 2001 the Council readjusted the fault model for the Tokai Eq. which is also shown in Fig.2. The Headquarters for Earthquake Research Promotion (HER, 2001) also presented the model for the Tonankai Eq. as shown in Fig.2. They have been estimated on the basis of the recent advancement of the seismic observation and GPS technologies.

In Table 1, the fault parameters for these scenario earthquakes and their coupled earthquake (successive occurrence of the Tounankai and Tokai Eq.) are listed. They are both a reverse dip-slip fault with the dip angle of 11.54 degree for the Tounankai and 16.4 degree for the Tokai Eqs. The moment magnitude is M_W=8.2 for the Tounankai and M_W=8.0 for the Tokai Eqs, respectively, and in the case for their coupled one, M_W=8.3.

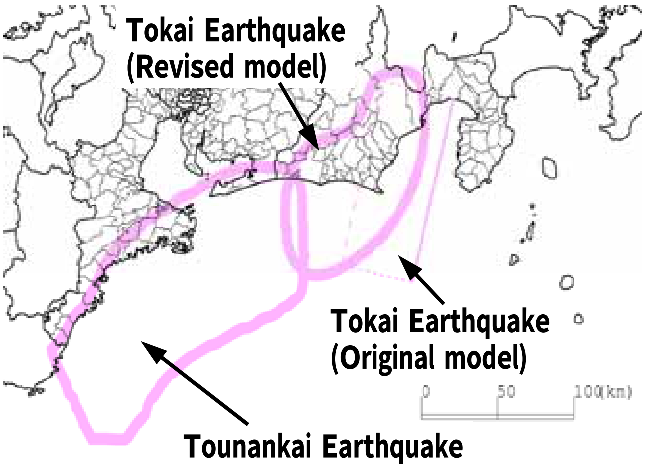

Fig.2 Location of Tokai and Tounankai Faults

Table.1 Fault Parameters of Scenario Earthquakes.

		Tokai Earthquake	Tounankai Earthquake	Coupled Earthquake with Tokai and Tounankai
Hypocenter	Latitude	34° 12'10"	33° 36'00"	
	Longitude	137° 56'20"	136° 07'12"	
Fault Plane	Length L (km)	145*	200*	145*+200*
	Width W (km)	70*	100*	70*+100*
	Area S (km^2)	7536**	14688**	21912**
	Strike θ (degree)	207.0	232.0	-
	Dip Angle δ (degree)	16.4	11.54	-
Seismic Moment M_0 (N m)		1.10×10^{21}	2.15×10^{21}	3.25×10^{21}
Moment Magnitude M_W		7.96	8.15	8.27
Propagation Velocity of Fault Rupture v_r (km/sec)		2.71		
Shear Wave Velocity V_{prop} (km/sec)		3.82	3.80	

3. SIMULATION OF STRONG GROUND MOTION ON ROCK SURFACE

3.1 Simulation Technique

It is one of the fundamental subjects in the field of earthquake engineering to predict ground motion time history at a specific site for given fault parameters. There still remain unclear subjects in the prediction of short period ground motions even the strong motion records at near fields have been accumulated and they have been analyzed carefully.

Table 2 gives the classification and characteristics of ground motion prediction technique. They were classified into 3 categories : simple prediction models for peak ground motion parameters such as a peak acceleration, a peak velocity, and spectral intensities (category I), prediction of ground motion time history on the basis of the synthesis of ground motion or spectral intensities from sub-event on or near fault (category II), and FEM-based dynamic analysis from source to site (category III).

Table 2 Classification and characteristics of ground motion prediction techniques

	category	technique	required parameters	estimated ground motion parameters	appried examples	remaining problems
I	**attenuation equation of peak ground motion**	empirical formula as a function of magnitude and source-to-site distance	magnitude M, distance R (epicentral, hypocentral, shortest to fault, etc.)	peak acc. vel., and spectral intensity such as response spetrum	design load for peak ground motion design spectrum seismic risk analysis	large prediction uncertainty (δ =40 ～ 60 %) strong effect of local geology
II	**synthesis of ground motion or spectral intensity from sub-event in or near main fault**	(1) spectral intensity*1	M, R, fault size, etc.	response spectrum	design spectrum, etc.	large prediction uncertainty (δ =40 ～ 60 %)
		(2) ground motion from sub-event in or near main fault*2	records from sub-event, seismic moment, M_0, fault size, rupture velocity, etc.	ground motion time history	ground motion time history for seismic design, etc.	prediction uncertainty is unknown, site record from sub-event is indespensable
		(3) evolutionary power pectral from sub-event in main fault*3	seismic moment, M_0, fault size, rupture velocity, etc.	ground motion time history	ground motion time history for seismic design, etc.	large prediction uncertainty (δ =40 ～ 60 %)
III	**FEM-based dynamic analysis from source to site**	(1) FEM-based dynamic analysis ・discrete wave-number method*4 ・FEM-based dynamic analysis ・stress-relaxation model*5 (2) continum model	detailed fault parameters (fault size, dislocation, rupture pattern, source time function, tress drop, two or three dimensional soil structure model from source to site, etc.)	ground motion time history	ground motion time history for seismic design, etc.	detailed fault parameters are needed, prediction uncertainty is unknown

*1 Midorikawa,S. and Kobayashi,Y. (1979). *2 Irikura,K. (1986). *3 Sugito, M., Furumoto, Y. and Sugiyama, T. (2000).
*4 Toki,K. and Miura,F. (1985). *5 Yamada,Y. and Noda,S. (1986).

In general terms the simulation techniques of ground motion time history developed by now may be classified into the following three categories.

(1) FEM-based dynamic computation [Table 2, III-(1)]
(2) Hybrid simulation based on the principle of similitude in the fault parameters and strong motion records at the site (so-called empirical Green's function method [Table 2, II-(2)]
(3) Synthesis of the ground motion time histories or evolutionary power spectra which correspond to those for sub-event on the main fault [Table 2, II-(3)]

It is an essentiality in the engineering aspect to select the simulation technique depending on the amount of information on given fault parameters. In the case for the Tokai or

Tounankai Earthquake, the fault parameters such as geometrical parameters, rupture velocity, asperity distribution, and other related parameters are given. However, the detailed profiles on three dimensional structure to deep rock basement and dynamic properties of the fault have not been specified. Considering these situation, the simulation technique should be selected. In the following, the simulation technique, EMPR (Sugito *et. al*., 2000) was applied, in which the ground motion time history is simulated on the basis of the synthesis of the evolutionary spectra (Kameda, 1975) from each individual sub-event equally distributed on the main fault.

3.2 Fault Model

On the basis of the fault models which have been presented by the National Disaster Prevention Council, Japan (2001) and the Headquarters for Earthquake Research Promotion (2001), the fault parameters are identified for the simulation of strong motion by the technique, EMPR. In this technique, the acceleration time history from the given fault is simulated on the basis of the synthesize of the evolutionary power spectra which corresponds to each individual sub-event equally divided on the fault. To incorporate the effect of the asperity distribution on the fault into the ground acceleration time history, the following process is applied.

The asperity is generally identified as the area where dislocation is relatively large, and it represents, in consequence, the distribution of seismic moment over a fault. In the EMPR, the number of superposition, N_G, is scaled from the given seismic moment, M_0. The superposition number, N_G, represent the number of sub-event which corresponds to the earthquake of M=6.0. The empirical relation was given in the following.

$$N_G = 6.35 \times 10^{-8} \times M_0^{0.409} \tag{1}$$

in which the seismic moment, M_0, is given by

$$M_0 = \mu \cdot D \cdot S \tag{2}$$

where μ denotes shear rigidity (N/m^2), D and S denote the dislocation (m) and area of fault (m^2), respectively. The asperity for the scenario earthquake is given as the distribution of local dislocation over the fault. Consequently, it can be substituted for the distribution of local seismic moment, in condition that shear rigidity is constant over the fault. Considering the relation given by Eq.(1), the relation between the number of superposition, N_G, and dislocation, D, is given by,

$$N_G \propto D^{0.409} \tag{3}$$

This relation is consistent when the area of fault and the shear rigidity is equal. In the technique EMPR, a fault is equally divided into some number of sub-events. The distribution of dislocation on a fault is converted into that of relative ratio of acceleration power release which is obtained by using the relation of Eq.(3). Namely, the relative dislocation ratio on a fault is converted into that of acceleration power release in proportion to $D^{0.409}$.

Fig.3 shows the schematic description of the asperity pattern for the simulation by EMPR with the original asperity locations (NDP, HER, 2001). Table 3 gives the expected local slip (dislocation) distribution (NDP, HER, 2001) and asperity pattern for the simulation by EMPR, which represents the relative ratio of acceleration power release on a fault.

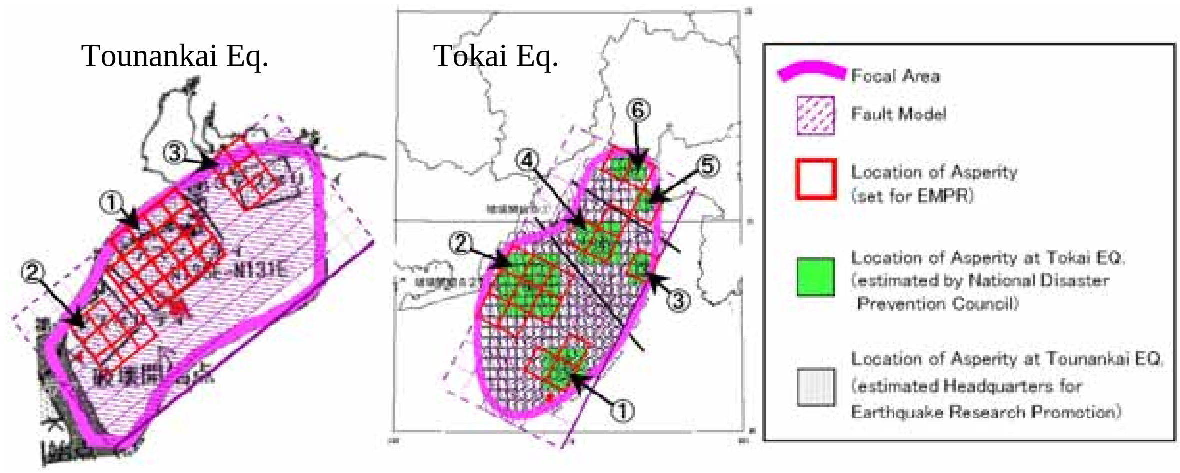

Fig.3 Fault Model and Asperity Distribution for Tokai and Tounankai Earthquake.

Table 3 Relative Power Ratio of Sub-event.

(a) Tounankai Earthquake

Area(Show Fig.3(a))	①	②	③	Back Ground
Slip(m)	8.50	6.01	6.01	2.08
Relative Power Ratio	1.78	1.54	1.54	1.00

(b) Tokai Earthquake

Area(Show Fig.3(b))	①	②	③	④	⑤	⑥	Back Ground
Slip(m)	4.80	6.93	3.35	4.84	2.78	3.90	1.78
Relative Power Ratio	1.50	1.74	1.29	1.51	1.20	1.38	1.00

3.3 Simulation of Rock Surface Strong Motion for the Scenario Earthquakes

For the given fault parameters shown in Fig.3 and listed in Table 1 and 3, the ground motions on rock surface revel were simulated. Fig.4 shows the location of simulation site which is Port of Nagoya, the location of focus and asperity distribution of scenario earthquakes, and the simulated acceleration time histories as well as the example of strong motion record during the 1995 Hyogoken-Nambu Earthquake. In the upper of right hand side of Fig.4, the original fault model of Tokai Eq., its revised one, and Tounankai Eq. are shown with their focus. The lower one represents the fault model for Tounankai-Tokai coupled Eq.

In the left hand side of Fig.4, the simulated accelerations for scenario earthquakes as well as the rock surface strong motion during 1995 Hyogoken-Nambu Eq. of M=7.2 are plotted. Their simulation cases are as follows. The parameters, R, Rs, and L represent hypocentral distance, shortest distance to a fault, and fault length, respectively.

(a) modified rock surface acceleration at Shin-Kobe substation of Kansai Electric Power Co.
[M=7.2, R=30 km, fault length L=40km]
(b) simulated acceleration for the original fault model of Tokai Eq.
[M_W=7.9, R=174 km, Rs=120 km, L=120 km]
(c) simulated acceleration for revised fault location model of Tokai Eq. with no asperity distribution
[M_W =8.0, R=138 km, Rs=86 km, L=145 km]
(d) simulated acceleration for revised fault model of Tokai Eq.

[M_W =8.0, R=138 km, Rs=86 km, L=145 km]
(e) simulated acceleration for fault model of Tounankai Eq.
[M_W =8.2, R=171 km, Rs=49 km, L=200 km]
(f) simulated acceleration for fault model of Tounankai-Tokai coupled Eq.
[M_W =8.3, R=171 km, Rs=49 km, L=345 km]

In the comparison (b) and (c), the effect of site-to-fault distance is clearly shown. The effect of asperity distribution to ground motion is demonstrated in the comparison of (c) and (d). In case of (d), the strong asperity is given on the fault near to Nagoya site, and the effect of the asperity location is observed in the acceleration envelope on the time axis. In the case (e) for the Tounankai Eq., the fault rupture propagates in the direction to the site, therefore, the acceleration power is relatively accumulated on time axis. Consequently, the peak acceleration gets relatively high and duration of strong motion becomes shorter than that in the case (d). In the case (f) for Tounankai-Tokai coupled Eq., as the matter to be expected, the duration of strong shaking becomes very long, and it is more than 90 seconds.

As shown in the simulated strong motions for several huge scenario earthquakes, it is one of the important engineering characteristic that the duration of strong motion is appreciably long, such as more than 60 seconds, depending on fault size. In this case a peak ground motion parameters such as a peak acceleration, velocity, and the JMA intensity etc., are not enough indices for estimation of seismic disaster.

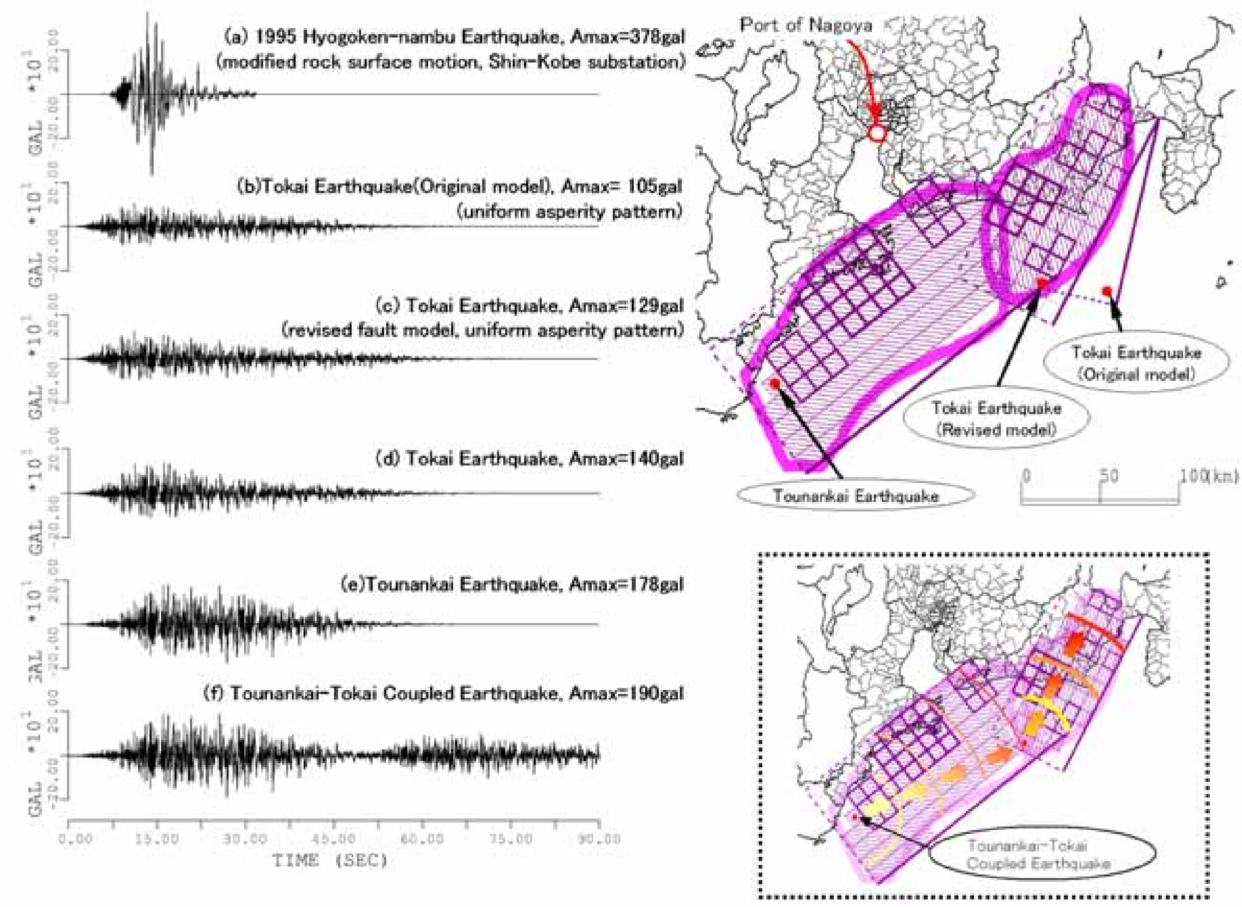

Fig.4 Comparison of Acceleration Time Histories at Nagoya Port Site and Recorded from the 1999 Hyogoken-Nambu Eq.

4. JMA SEISMIC INTENSITY MAP AND DESTRUCTIVENESS OF EARTHQUAKE

4.1 Database for Soil Profile Models

The strong effect of surface geology on ground motion intensity have been frequently observed both in strong motion records and seismic disaster appearances. The information on soil profile over base rock is indispensable for ground motion estimation on soil surface. It should be realized that the database for soil profile models over the concerned area is required for the detailed seismic intensity map for scenario earthquakes.

After the 1995 Hyogoken-Nambu Eq., most of prefectural governments in Japan have individually surveyed soil exploration data and developed the database for the soil profile models which covers their prefectures. Since the damaged area for the huge earthquakes spread over the prefectures, the soil profile data for 6 prefectures in Tokai region are arranged and used. Table 4 shows the database of soil profile models for 6 prefectures in Tokai region. Generally the soil profile model is assigned for each individual mesh (approximately 500 x 500 meters mesh), and the number of models differs in prefectures. The database includes soil profile models assigned for approximately 180,000 mesh points.

On the basis of the database, the feature of surface geology in this wide area can be analyzed. Fig.5 shows the map of the soil softness index, *Sn*, which is a continuous number and represents the softness of surface geology to the depth approximately GL.-20m. The parameter *Sn* is defined in the following.

$$S_n = \int_0^{ds} e^{-0.04N(x)-0.14x}dx - 0.885 \qquad (4)$$

where N(x) and ds denote the blow-count and the depth of soil profile data, respectively. The numerals in Eq.(4) have been obtained statistically so that the parameter Sn represents properly the effect of soil softness on ground motion amplification.

Table 4 Database of Soil Profile Models for 6 Prefectures.

Prefecture	Mesh size (m)	No. of mesh	No. of soil profile models
Aichi	500×500	20,345	49
Gifu	500×500	41,461	316
Mie	1000×1000	6,015	13
Shizuoka	500×500	30,272	10
Nagano	500×500	53,174	647
Yamanashi	500×500	17,491	9

4.2 Response Analysis of Sub-surface Ground

The seismic response analysis for the multi-layered surface ground model were carried out for all over the area for three scenario earthquakes. The program code, FDEL, which incorporates the effect of frequency dependent equivalent strain characteristics on the shear rigidity and damping (Sugito *et al*. 1993), was applied for the analysis. The ground motion parameters such as peak acceleration, peak velocity, as well as the JMA seismic intensity, were obtained for the scenario earthquakes.

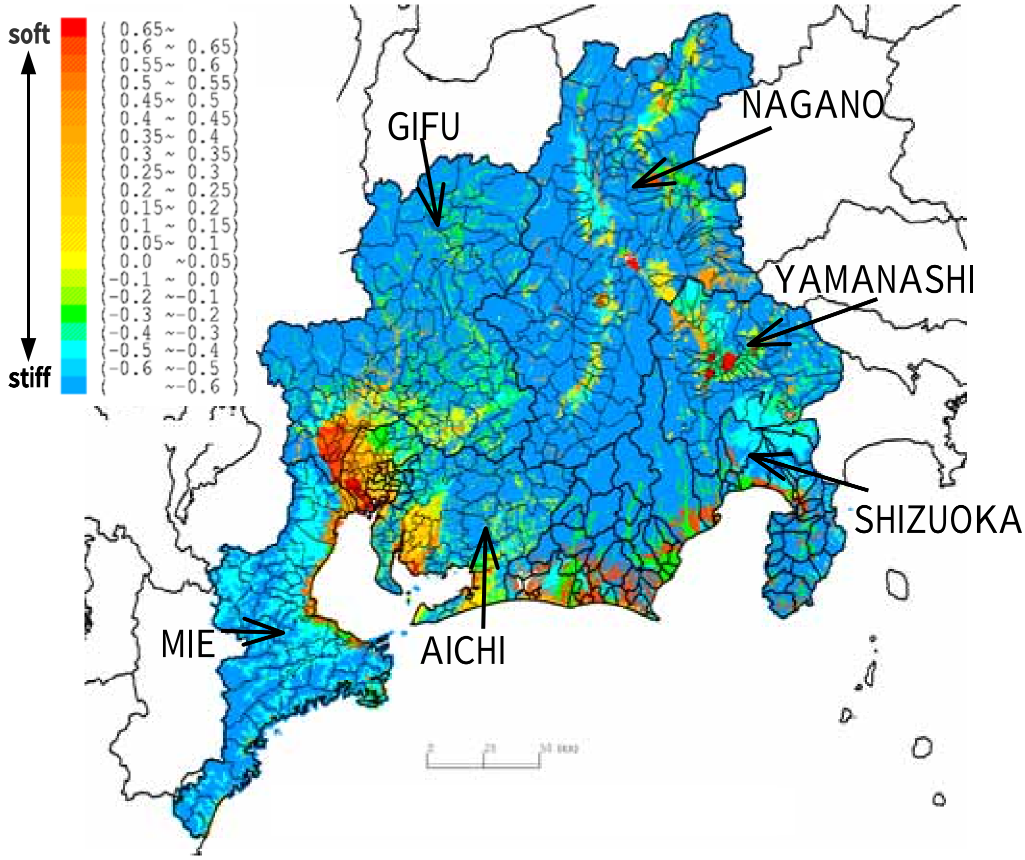

Fig.5 Distribution of the Index, *Sn*, showing Softness of Soil Surface in Tokai Region.

After the 1995 Hyogoken-Nambu Earthquake, the Japan Meteorological Agency started to announce the intensity value obtained by a seismometer at each city and local district just after the earthquake occurrence. The value is called the JMA seismic intensity scale, and the scale is derived from the continuous values into the 10-fold intensity scale ranging from 0 to VII. Fig.6 compares the JMA seismic intensity scale and MMI (Modified Mercalli Intensity) scale.

The JMA seismic intensity for scenario earthquakes were obtained from the simulated acceleration time histories at more than 170,000 points in the area. Fig. 7 shows the JMA seismic intensity map for the Tounankai-Tokai coupled earthquake with the location of the fault. The following typical characteristic regarding the distribution of seismic intensity could be recognized.

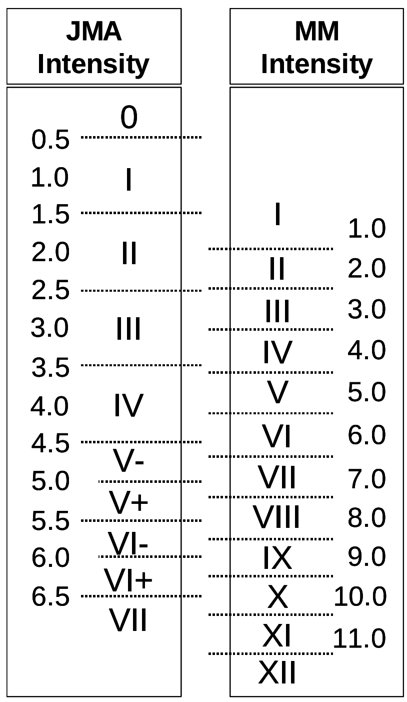

Fig.6 Relationship between JMA and MMI Intensities.

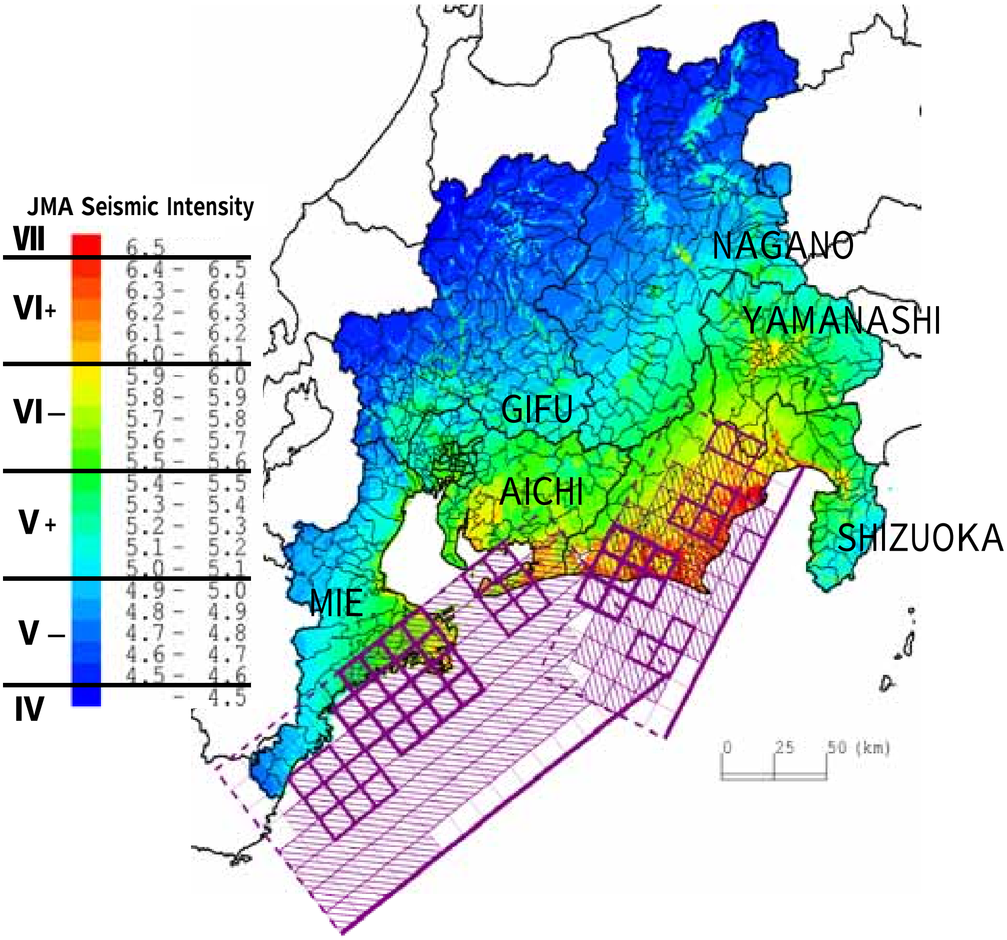

Fig.7 JMA Seismic Intensity Map for Scenario Tounankai-Tokai coupled Earthquake.

(1) source-to-site distance effect : high seismic intensity at sites where the source-to-site distance is short (south part of Shizuoka and Aichi prefecture)
(2) local geology effect : the ground motion is amplified strongly in soft surface ground (it is clear in the comparison of Fig.5 and Fig.7)
(3) directivity effect : the power of strong motion is accumulated at sites to which the rapture front comes close (south of Yamanashi and east of Shizuoka prefectures)

4.3 Evaluation of Seismic Destructiveness

The two indices were examined for approximate measure of seismic destructiveness for scenario earthquakes. One is the area, *AEX*, which represent the area exposed to some JMA seismic intensity scale. This index indicates how the area of some damage level is spread. Another index is *PEX*(population exposure to seismic intensity) proposed by Nojima et al.(2002), and this index indicates how many people are exposed to some seismic intensity level. The seismic disaster regarding physical damage to human could be evaluated by the index, *PEX*.

The JMA seismic intensity map for 3 scenario earthquakes were obtained, and the destructiveness of these earthquakes were compared by the two indices explained above. Fig.8 shows these indices for 3 scenario earthquakes as well as the 1995 Hyogoken-Nambu Earthquake. In Fig.8(a), where the area for each seismic intensity level, *AEX*, is compared, the total area of JMA VI-, VI+, and VII (VIII to XI in MMI scale) for the three scenario earthquakes is much larger than that for Hyogoken-Nambu Earthquake which was an inland earthquake and fault length was less than 40 km. From these comparison, it is clear that the severely damaged area for the scenario earthquakes will be spread much wider than that for the inland earthquake, such as the 1995 Hyogoken-Nambu Eq.

The index, *PEX*, for these earthquakes is shown in Fig.8(b). In contrast to Fig.8(a), the total of the *PEX* for JMA VI-, VI+, and VII for the 1995 Eq. does not differ from that for the Tokai and the Tounankai Eqs., since this inland earthquake occurred in Hyogo prefecture and the city of Kobe was attacked severely. The result shown in Fig.8 indicates that the seismic disaster will be spread over in vast area, and a large number of people would be injured or killed in wide area. Consequently, it would take considerably long time for rescue and restoration. This is one of the characteristic aspect of seismic disaster for the huge subduction earthquakes.

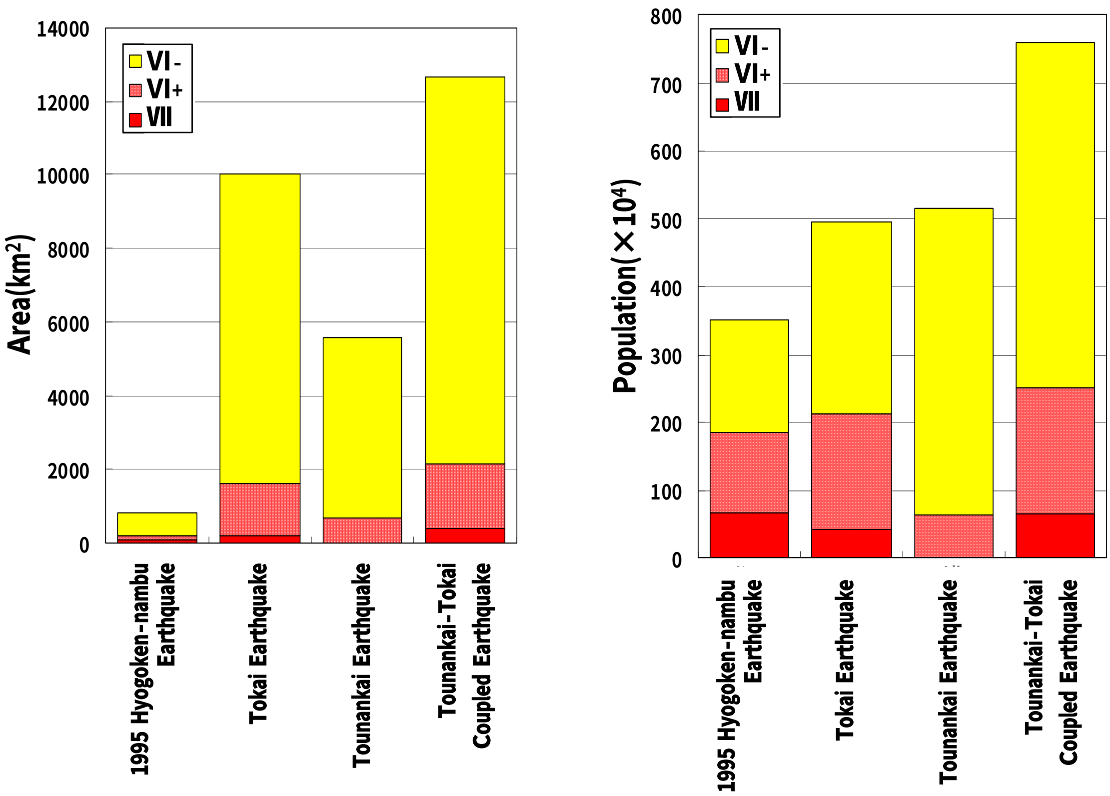

Fig.8 Comparison of Area and Population Exposure to Seismic Intensity for Scenario Huge Earthquakes and 1995 Hyogoken-Nambu Eq (Nojima, *et al*., 2004).

5. CONCLUSIONS

This paper presents the estimation of extensive distributions of seismic intensity in Tokai region in Japan, for the huge scenario earthquakes in the Nankai Trough region. The major conclusions derived from this paper may be summarized as follows.

1) The seismicity of Tokai region in Japan, which is the most active region regarding huge earthquake occurrences in the world, was introduced. The fault models for three scenario earthquakes were characterized according to the survey on the seismicity and earthquake prediction by the National Disaster Prevention Council, Japan*** and the Headquarters for Earthquake Research Promotion
2) The simulation technique of strong ground motion were reviewed and classified regarding their method and required parameters on fault and source-to-site ground conditions.
3) The ground motion simulation in the wide area were carried out for the three scenario earthquakes. The two techniques developed by the authors were used; one is the simulation technique, EMPR, for non-stationary strong motion time histories on the upper surface of so-called engineering basement rock, and the other is the seismic response analysis for the multi-layered surface ground model, FDEL, which incorporates the effect of frequency dependent equivalent strain characteristics on the shear rigidity and damping. The soil structure models were used to incorporate the effect of surface geology on ground motion.
4) The typical characteristics on the seismic intensity distributions for the three hypothetical earthquakes were derived, and the areas of severe seismic intensities were compared in the three hypothetical earthquakes and those during the 1995 Hyogoken-Nambu Earthquake. Another index, PEX(population exposure to seismic intensity), was also examined for these earthquakes demonstrating the destructiveness of the earthquakes against the regional society as a whole.

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