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PROBABILISTIC DESIGN EARTHQUAKE GROUND MOTIONS CONSIDERING SCENARIO EARTHQUAKES

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SUMMARY

A procedure is proposed to generate design earthquake motions considering scenario earthquake data for any life-time probability of exceedances in particular in the range of 10^{-2} to 10^{-3}. We applied the procedure to the KiK-net site of Shizugawa in Miyagi Prefecture, Japan as an example site, with fairly sufficient information on the earthquake occurrence model and earthquake motion records. Ground motions were simulated for the Miyagi-ken Oki earthquakes with magnitudes of 8 and 7 to form a portion of probabilistic seismic hazard curves.

INTRODUCTION

In the conventional earthquake resistant design of nuclear power plants in Japan, the input earthquake ground motions are generated according to the design spectra specified with magnitudes and distances. Neither the exceedance probability nor the fault parameters are explicitly indicated in the current design spectra. Recent seismological developments have enabled us to estimate fault parameters and also the probability of occurrence for major active faults in Japan. It is desirable to take into these parameters for the design earthquake ground motions (Dan *et al.*[1]).

On the other hand, the performance-based design is discussed for all kinds of structures to provide a quantitative measure for the safety and serviceability criteria. The seismic safety is not exceptional and the determination of the safety goal becomes a societal requirement for the management of nuclear power plants. The target safety measure is a common international problem rather than national matters.

More than a few probability seismic hazard maps are available, but the findings for scenario earthquake faults are not taken into account. The purpose of this study is to propose a procedure to generate design earthquake motions considering scenario earthquake data for any life-time probability of exceedances in particular in the range of 10^{-2} to 10^{-3}. Number of simulations is limited in this study, but the framework of procedure is discussed for its usefulness.

FLOW CHART OF PROCEDURE

At first, we select an example site where we have sufficient information on earthquakes and ground motions for the purpose of simulations. As shown in Figure 1, we perform a preliminary probabilistic seismic hazard analysis for the site of interest based on the earthquake occurrence model and the attenuation relations among peak velocities, magnitudes, and distances, and selected scenario earthquakes based on deaggregation by Kameda *et al.* [2].

Next, we consider fault rupture scenarios in the scenario earthquakes, and evaluate the occurrence probability of each fault rupture scenario. Then, we assume fault models accordingly to the fault rupture scenarios to simulate ground motions. Since each simulated ground motion has its probability of occurrence, by assembling all possible ground motions, preliminary hazard curves can be replaced by those based on scenario earthquakes with more detailed information. Once seismic hazard curves are formed, design earthquake ground motions can be selected at required exceedance probabilities corresponding to specified criteria. The response spectrum measure may be preferred to the peak ground acceleration or velocity.

EXAMPLE SITE

The accuracy of the information on the active faults and the earthquake occurrence varies at present in Japan, and the uniform accuracy cannot be expected in calculating seismic hazard curves. Hence, in this study, we chose an example site where we could calculate a seismic hazard curve including rare strong ground motions in the following two view points of the earthquake occurrence model and the strong motion prediction procedure.

We focused on how to consider the scenarios of the fault ruptures, and categorized the earthquakes in and around Japan as follows[3]:

Category I : inland earthquakes caused by active faults recognized on the surface,
Category II: large plate boundary earthquakes in the subduction zones,
Category III: large slub earthquakes in the subducting plates,
Category IV: inland earthquakes caused by blind faults not recognized on the surface,
Category V: moderate or small plate boundary earthquakes in the subduction zones,
Category VI: moderate or small slub earthquakes in the subducting plates.

It is preferred that the example site is located in the region where all the six categories of the earthquakes occur because of easy extension of the methodology to other sites.

On the other hand, the accuracy of the strong motion prediction is expected to be improved when the earthquake records are observed at the site, because we can examine the source and path characteristics based on the records.

Consequently, we chose the KiK-net site of Shizugawa, Miyagi Prefecture, because the National Research Institute for Earth Science and Disaster Prevention [3] proposed the earthquake occurrence model in and around Miyagi Prefecture and also because good records have been available at this site. Figure 2 shows the active faults (Category I) and the source areas of the large plate boundary earthquakes (Category II) taken from Okumura *et al*. [4].

PRELIMINARY SEISMIC HAZARD ANALYSIS

We carried out a preliminary seismic hazard analysis to select scenario earthquakes, using peak velocities as ground motion intensities. We adopted an attenuation relation among peak velocities at the surface, magnitudes, and distances by Si and Midorikawa [5] and a correction factor for local path effects in northern Japan by Morikawa *et al*. [6], modeling the variation by the log-normal distribution with the logarithmic standard deviation of 0.53. Here, we evaluated the soil amplification factor from the engineering bed rock to the surface by Matsuoka and Midorikawa [7]. Figure 3(a) shows the results of the 50-year probability exceedance of the peak velocity. Figure 3(b) shows the deaggregation results: the contribution of each group of earthquakes, clearly indicating that the Miyagi-ken Oki earthquakes of Category II are predominant in the wide peak velocity range.

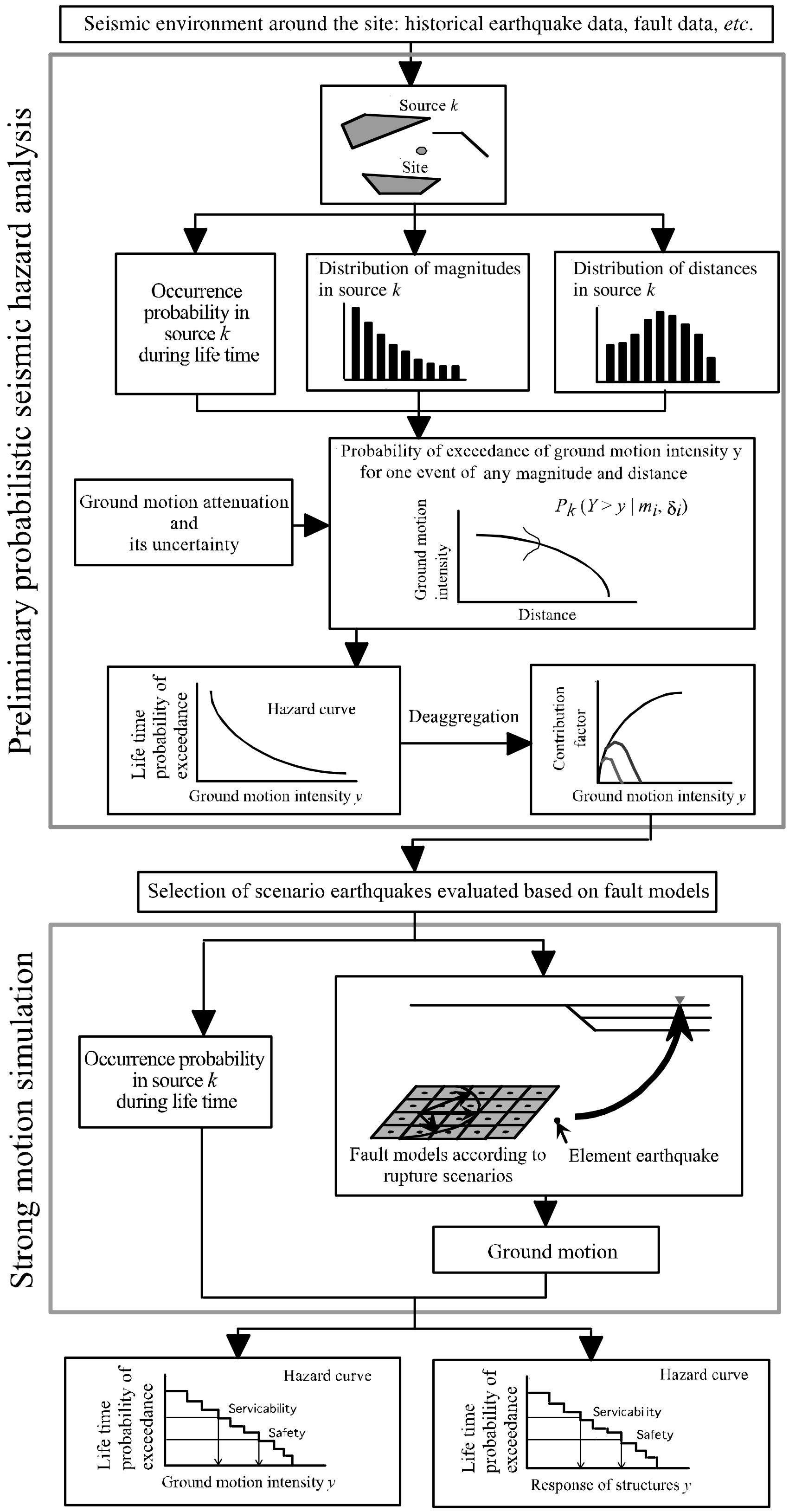


Figure 1. Flow chart for proposed procedure

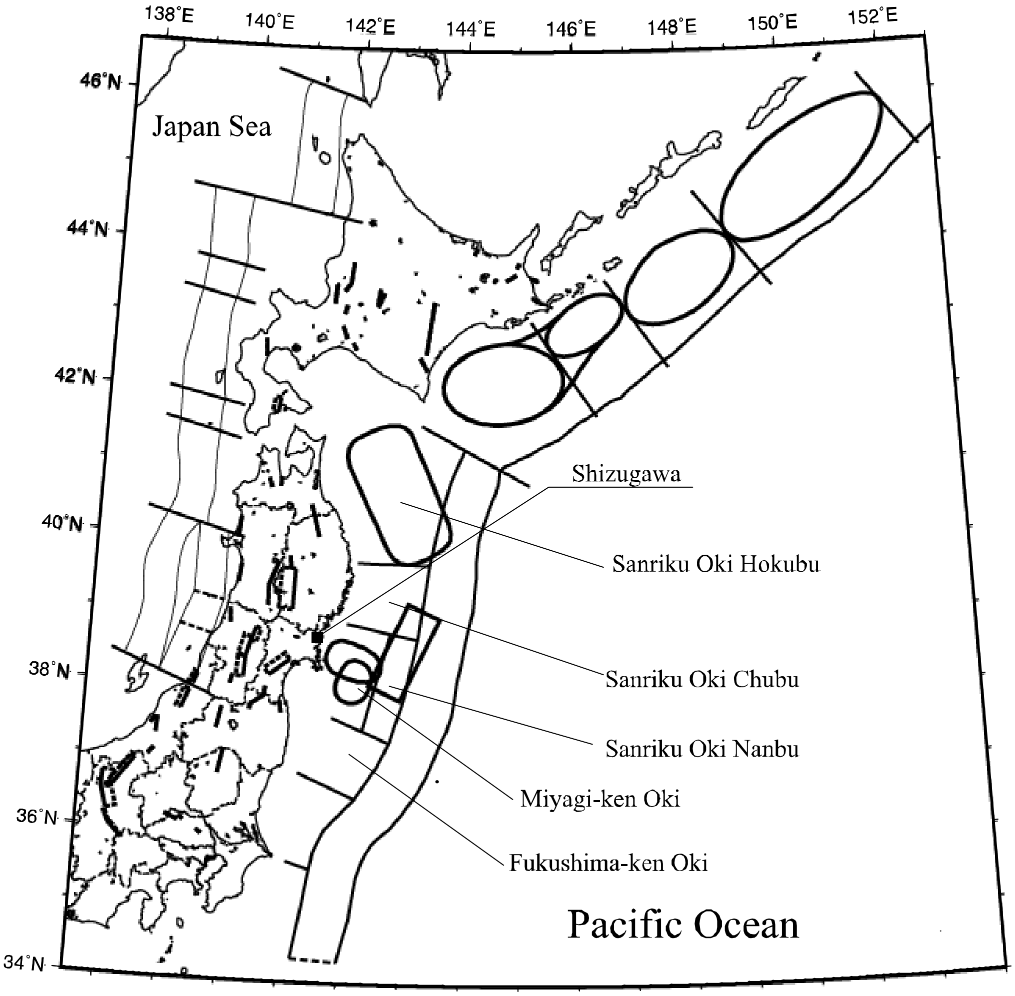


Figure 2. Location of the active faults and the source areas of large plate boundary earthquakes (after Okumura et al., [4])

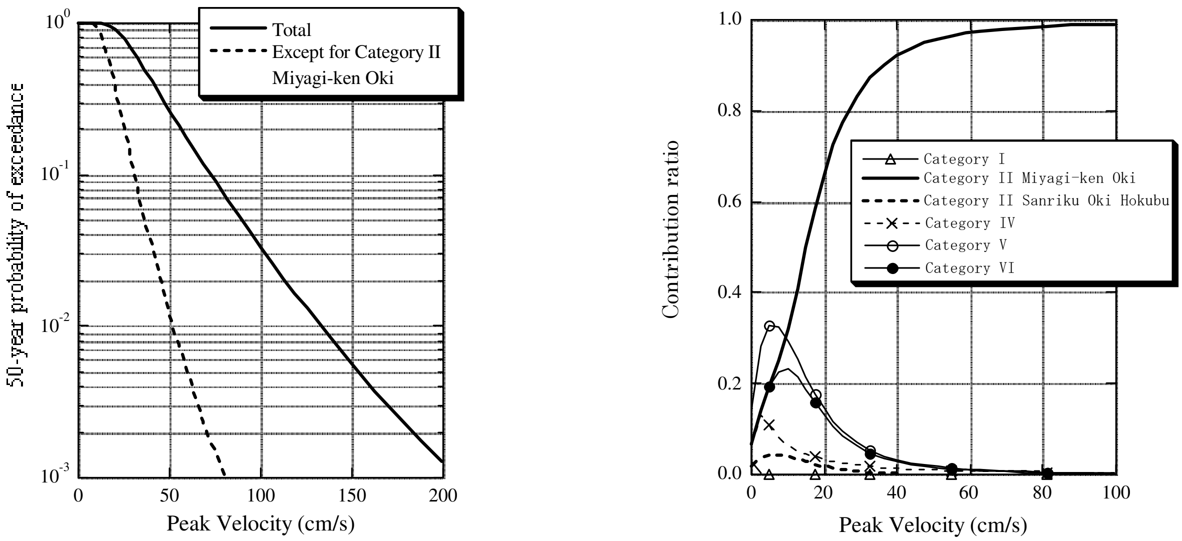
SELECTION OF SCENARIO EARTHQUAKES AND THEIR FAULT MODELS

Selection of scenario earthquakes

The preliminary results of the probabilistic seismic hazard analysis in Figure 3 indicated that the Miyagi-ken Oki earthquakes of Category II were predominant and that moderate or small earthquakes of Categories IV, V and VI were not negligible.
In order to show some results by the flow chart in Figure 1, we prepared fault models for earthquakes with a magnitude of 8 in Category II and with a magnitude of 7 in Category V, and simulated earthquake ground motions based on these fault models.

Scenarios of fault ruptures and their occurrence probabilities

We adopted scenarios of the fault ruptures in the Miyagi-ken Oki earthquakes with a magnitude of 8 in Category II proposed by the National Research Institute for Earth Science and Disaster Prevention [3]. The National Research Institute for Earth Science and Disaster Prevention assumed scenarios of the fault ruptures in the areas A1, A2, and B shown Figure 4 and some combinations of the three areas. The scenarios and the magnitudes were assumed as follows:



(a) Hazard curve (b) Deaggregation

Figure 3. Preliminary results of probabilistic seismic hazard analysis at the KiK-net site of Shizugawa for selecting scenario earthquakes

M_W =7.5 in the area A1 only,
M_W =7.4 in the area A2 only,
M_W =7.8 in the area B only,
M_W =8.0 in the area A1 + B,
M_W =8.0 in the area A2 + B,
M_W =8.1 in the area A1 + A2 + B.

We chose the top scenario of the area A1 only among the six scenarios because this scenario is regarded as the same as the 1978 event and it is easy to verify the simulated motions. The occurrence probability of this scenario is calculated to be 0.55 in the next 50 years from the historical data [3].

On the other hand, we assumed scenarios of fault ruptures in the Miyagi-ken Oki earthquakes with a magnitude of 7 in Category V. Two possible scenarios were assumed, i.e. one is in the area west in A1 and the other is in the area east in A1, including one asperity of the two asperities in the area A1, shown as A1W and A1E in Figure 5.

The occurrence probability of each scenario was calculated to be 0.08 in the next 50 years from the historical data in this region indicated as Miyagi-ken Oki in Figure 2 [3].

Fault models for strong motion prediction

The fault model of the earthquake with a magnitude of 7.5 in the area A1 was assumed based on the Headquarters of Earthquake Research Promotion [7], consisting two asperities and background shown in Figure 6. The fault parameters were evaluated by the procedure of Irikura *et al.* [9].

On the other hand, the fault model of the earthquake with a magnitude of 7 in the area of A1W or A1E was assumed to have each asperity of A1 as shown in Figures 7 and 8, the fault parameters were evaluated of Irikura *et al.* [9] again. Table 1 shows the fault parameters of the earthquakes in the areas A1, A1W, and A1E.

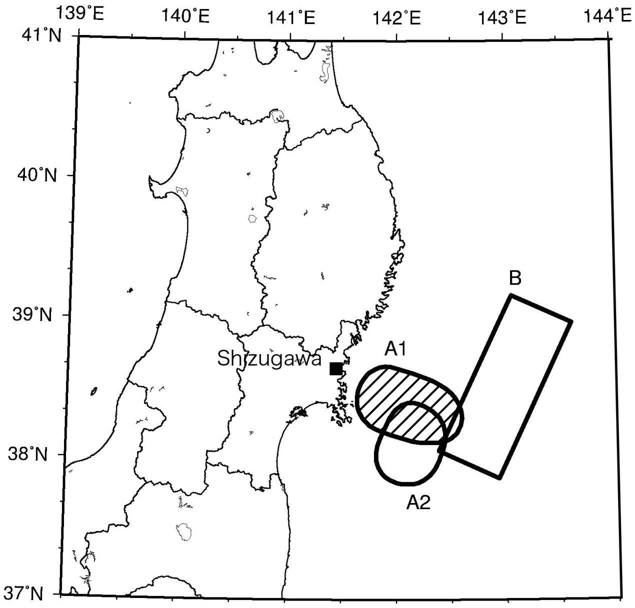


Figure 4. **Source areas of the Miyagi-ken Oki earthquakes with a magnitude of 8**

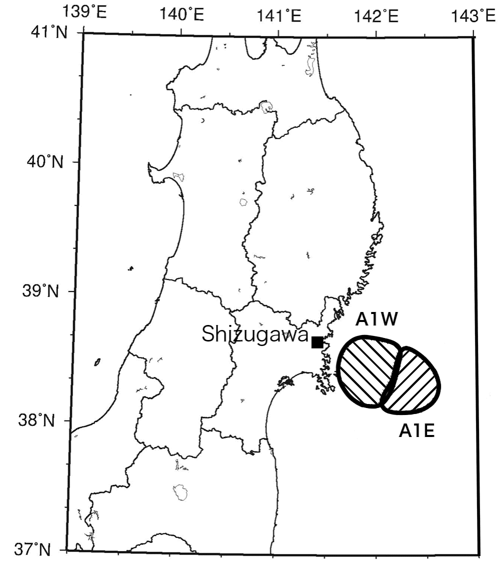


Figure 5. **Source areas of the Miyagi-ken Oki earthquakes with a magnitude of 7**

STRONG MOTION SIMULATION BASED ON FAULT MODELS

Records as empirical Green's functions

To predict the strong ground motions, we adopted a semi-empirical method [10] which is a method to calculate large earthquake motions by utilizing small earthquake records as empirical Green's functions. For reliable calculation of the large earthquake motions, the semi-empirical method needs small earthquake records in the source region for future earthquakes. Table 2 shows the parameters of the empirical Green's functions we selected based on these conditions.

Results of strong motion simulation

We synthesized large earthquake motions on the ground surface, using the empirical Green's functions and the fault models shown in Figures 6 to 8. Figures 9 to 11 show the acceleration motions, velocity motions, and the pseudo velocity response spectra for three cases of fault model respectively.

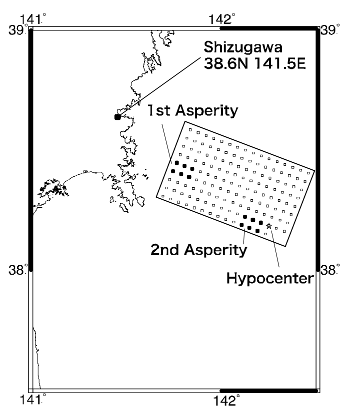


Figure 6. Fault model A1

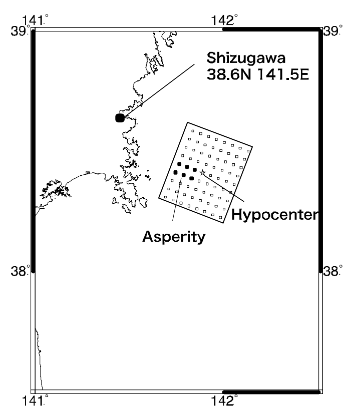


Figure 7. Fault model A1W

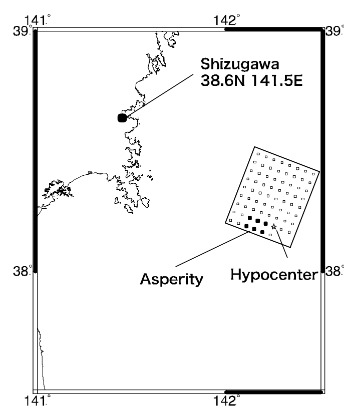


Figure 8. Fault model A1E

Table 1. Fault parameters of the earthquakes in the areas A1, A1W, and A1E

A1	Length, width	37.6 km, 67.0 km		
	Short-period level	9.1E+19 Nm/s^2		
	Moment magnitude	7.6		
	Occurrence probability	0.55 (occurrence probability in the next 50 years)		
		Asperity (west)	**Asperity** (east)	**Background**
	Seismic moment	2.6E+19 Nm	2.6E+19 Nm	2.6E+20 Nm
	Final slip	5.9 m	5.9 m	2.7 m
	Effective stress	290.0 bar	730.0 bar	68.0 bar
	Fault area	96km^2	96km^2	2074km^2
	Short-period level	3.1E+19 Nm/s^2	7.8E+19 Nm/s^2	3.4E+19 Nm/s^2
A1W	Length, width	18.8 km, 33.5 km		
	Short-period level	3.1E+19 Nm/s^2		
	Moment magnitude	7.0		
	Occurrence probability	0.08 (occurrence probability in the next 50 years)		
		Asperity		**Background**
	Seismic moment	6.5E+18 Nm		3.2E+19 Nm
	Final slip	1.4 m		0.65 m
	Effective stress	290.0 bar		16.5 bar
	Fault area	96km^2		1056 km^2
	Short-period level	3.1E+19 Nm/s^2		5.8E+18 Nm/s^2
A1E	Length, width	18.8 km, 33.5 km		
	Short-period level	8.0E+19 Nm/s^2		
	Moment magnitude	7.3		
	Occurrence probability	0.08 (occurrence probability in the next 50 years)		
		Asperity		**Background**
	Seismic moment	1.6E+19 Nm		7.9E+19 Nm
	Final slip	3.7 m		1.7 m
	Effective stress	726.0 bar		61.7 bar
	Fault area	96km^2		1024km^2
	Short-period level	7.7E+19 Nm/s^2		2.1E+19 Nm/s^2
Common	Strike, dip	21°, 17°		
	Rigidity of the medium	4.7E+10 N/m^2		
	S-wave velocity, rupture velocity	3.9 km/s, 3.0 km/s		

Origin time	2002/May/6/17:12:00(Japan Standard Time) [11]
Latitude, longitude, depth	38.46N, 142.15E, 40 km [11]
Seismic moment	2.82E+16 Nm [12]
JMA Magnitude	5.0 [11]
Length, width	2.4 km, 2.4 km
Final slip	0.12 m
Effective stress	61 bars [13]
Short-period level	0.15E+19 Nm/s^2 [13]
Observation Site	KiK-net Shizugawa(38.64N, 141.45E), Miyagi Prefecture, Japan
Epicentral distance	65 km

SEISMIC HAZARD CURVES BY FAULT RUPTURE SCENARIOS AND DISCUSSIONS

Parts of seismic hazards based on scenario earthquakes are shown in Figure 12 measured in terms of (a) peak ground acceleration, (b) peak ground velocity and (c) response spectrum, i.e. pseudo velocity response spectrum at a period of 0.25 seconds with a damping rate of 5%. These are considered as improved hazard curves from the preliminary results shown in Figure 3. Uncertainties expressed by the

variability of attenuation formula can be reduced by the present simulated earthquake ground motion with more detailed fault models. Once the scenario earthquake based hazard model is formed, design earthquake ground motions can be selected corresponding to the specified probability of exceedance. For example, for an important structure, such as skyscrapers, public offices are to be designed by expert opinions, such as the reliability index β =2.5 will be used for the serviceability limit and 3.5 may be used for the ultimate limit. Corresponding probability of exceedance for the hazard is 2×10^{-2} ($\alpha\beta=2$) and 2×10^{-3} ($\alpha\beta=2.8$), with the separation factor of $\alpha=0.8$. Scenario-based hazard curves are supposed to be located between the hazard with attenuation variability and that with no variability in attenuation model, when the attenuation model is consistent to the simulated results based on scenario earthquakes.
Present results for simulated motions have rather high probability of exceedance as the occurrence probability of Miyagi-ken Oki earthquake is very high and rare combinations for fault parameters are not considered yet. Therefore it is only possible to provide an design earthquake ground motion for the serviceability limit is this example. Rare combinations of fault parameters for category II earthquake, other five case scenarios for category II earthquakes, some possible inland earthquakes with no fault information in category IV, and also earthquakes in other categories have to be examined to replace the whole hazard curve in the preliminary study by scenario based earthquakes.

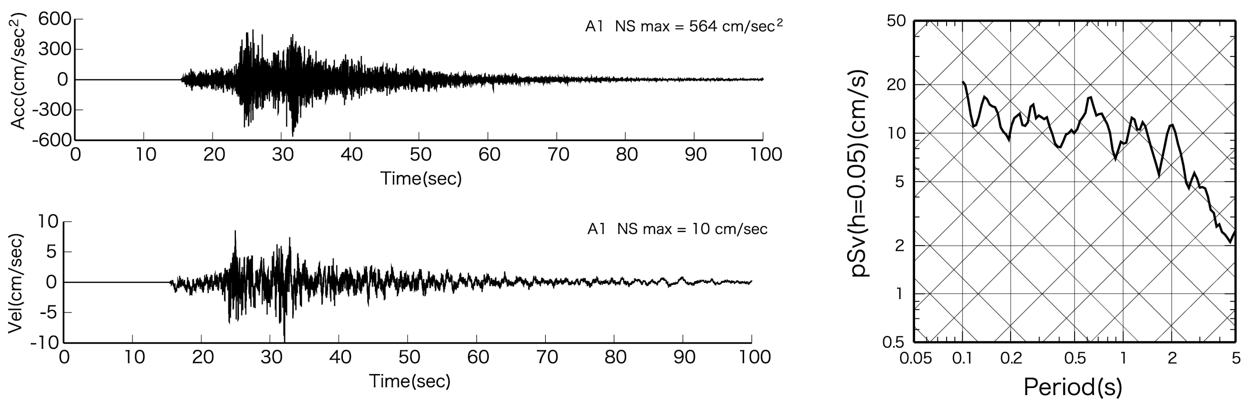


Figure 9. Results for the fault model A1

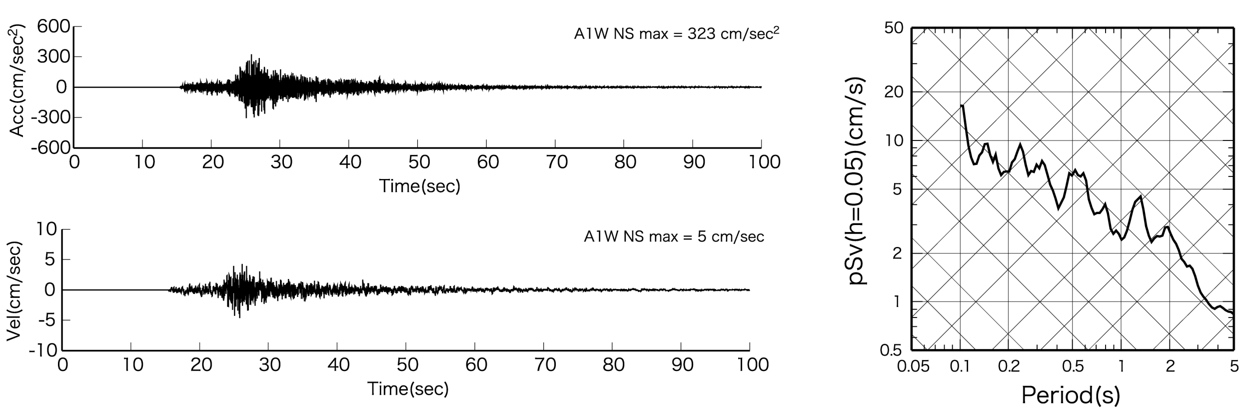


Figure 10. Results for the fault model A1W

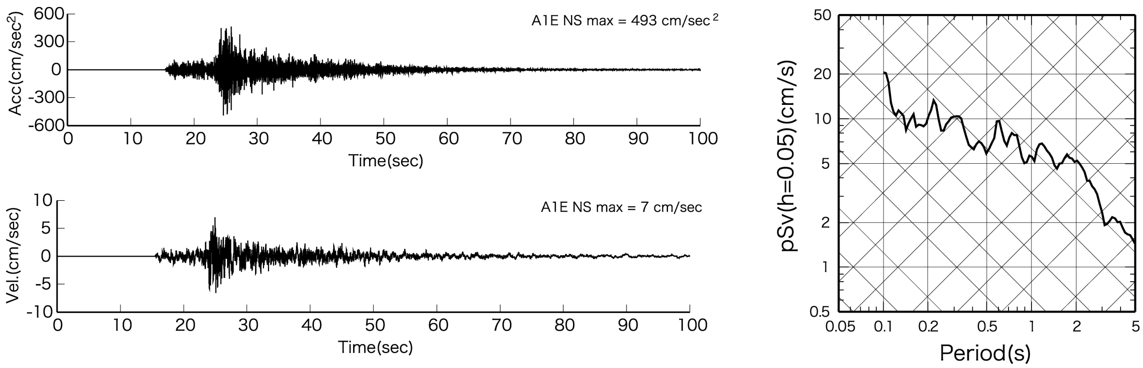
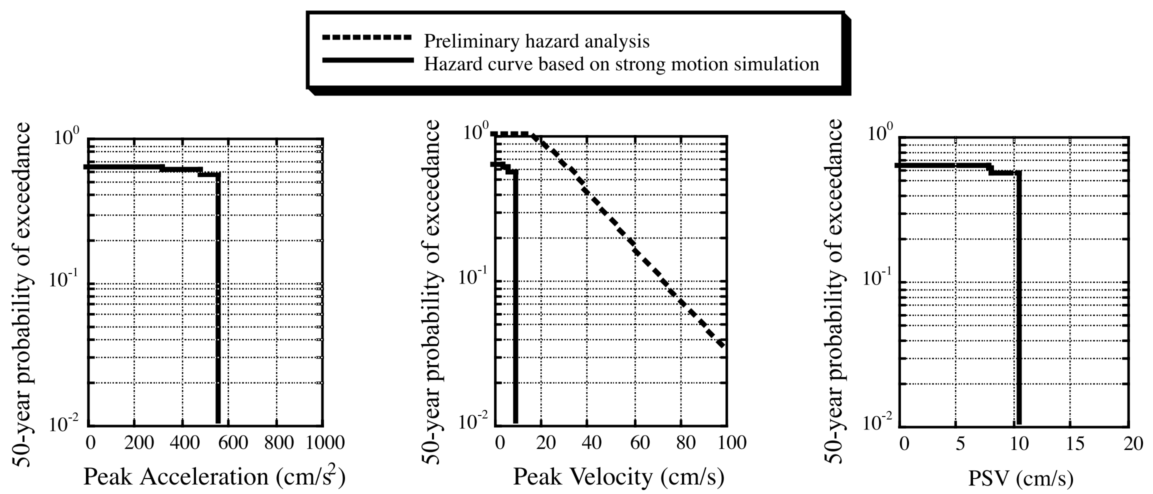


Figure 11. Results for the fault model A1E



(a) Peak Acceleration **(b) Peak Velocity** **(c) Response Spectrum (Period = 0.25 seconds)**

Figure 12 Hazard curves based on the earthquake ground motions by the fault rupture scenarios

CONCLUSIONS

A procedure for probabilistic design earthquake ground motions based on scenario earthquakes was proposed and simulated motions for an example site Shizugawa in Miyagi prefecture were presented according to a semi-empirical method. Although further efforts are needed to form a seismic hazard curve by scenario earthquakes, the proposed procedure is useful to combine detailed fault rupture information for the probabilistic design earthquake ground motion.

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