SIMULATION OF NON-STATIONARY STRONG GROUND MOTIONS DURING PAST EARTHQUAKES BASED ON THE FAULT PARAMETERS AND THE SPECTRAL CHARACTERISTICS OF RECORDED ACCELEROGRAM

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ABSTRACT :

With an analysis of observed earthquake record, a simulation procedure is presented for estimating strong ground motions at any site during past earthquakes. The spectral characteristics of recorded accelerogram from past earthquake are examined and incorporated into the strong motion prediction model which is called 'EMPR-II', which can simulate the non-stationary time-history on the rock surface by superposition of the evolutionary power spectra with the given fault parameters, such as the fault length and the width, the seismic moment, the rupture pattern of the fault and propagation velocity of seismic waves. Some simulations of eathquake motion during 2007 Niigataken Chuetsu-oki earthquake are presented for the purpose of investigating the structure damage.

KEYWORDS: evolutionally power spectrum, strong motion prediction model, non-stationary time-history, spectral characteristics of recorded accelerogram from past earthquake, 2007 Niigataken Chuetsu-oki earthquake

1. INTRODUCTION

Recently, earthquakes width strong motion consistently occurred in Japan, such as the Notohanto Earthquake in 2007 and the Niigataken Chuetsu-oki Earthquake in 2007. For the purpose of investigating the structure damage from these earthquakes, it is required that the input ground motion during the earthquakes on where the structure is build should be estimated correctly. Because the number of earthquake observation site is too limited to pinpoint the earthquake motions directly.

On the other hand, it is known that the non-stationarity of ground motion, such as the duration time and the envelope including its spectral characteristic, is differ from the characteristics of the earthquake, such as magnitude, focal depth and parameters of the hypocentral region. Therefore by analyzing earthquake records precisely, the common characteristics of the earthquake motions could be obtained.

The spectral characteristics of record from past earthquake are incorporated into the strong motion prediction model, which can simulate the non-stationary time-history on the rock surface by superposition of the evolutionary power spectra with the given fault parameters, such as the fault length and the width, the seismic moment, the rupture pattern of the fault and propagation velocity of seismic waves.

In this paper, the spectral characteristics of record from past earthquake are analyzed in the section3. In the section4, as a case study, the earthquake motion simulation is performed during 2007 Niigataken chuetsu-oki earthquake.

2. GENERAL SCHEME OF STRONG MOTION PREDICTION MODEL BY SUPERPOSING THE EVOLUTIONALLY POWER SPECTRA FROM SMALL EARTHQUAKE EVENT

Non-stationary strong motion prediction models are developed on the basis of rock surface strong motion dataset (Sugito, et.al., 2000). This models are dealt with the strong motion dataset consists of 118 components of major Japanese accelerograms including the records from the 1995 Hyogoken-nambu Earthquake. The input motion at an engineering foundation level with the shear wave velocity of vs =500-600 m/sec are estimated by the modified equivalent linearization technique in frequency domain which is called FDEL (Sugito, et.al., 1994). On the basis of the dataset, two types of prediction models are developed: the EMPR Model-I for given earthquake magnitude and hypo-central distance, and the Model-II for given fault parameters, such as fault length and width, seismic moment of fault, rupture pattern and rupture velocity, and propagation velocity of seismic waves. The EMPR Model-II incorporates the effect fault size, successive fault rupture, and rupture direction, on characteristics of ground motion. In the Model-II, the evolutionary power spectrum from large earthquake is calculated by superposing those from unit event which corresponds to the earthquake of M=6.0 in the Model-I.

2.1. Estimation of Free Rock Surface Ground Motion

Strong motion data used in EMPR consists of 118 components of acceleration time histories that have been obtained at 25 stations during 37 Japanese earthquakes. The modified equivalent linearization method for the response analysis of layered ground, which is called FDEL (Sugito, et. al., 1994), has been applied to obtain on free rock surface motions from observed records.

Fig.1 shows the scatter gram of magnitude and hypo-central distance of the dataset. In the Fig.1, 85'model represents the data which has been used in the previous paper (Sugito, et.al., 1985). 'PHRI data' represents the data obtained by the Port and Harbor Research Institute, Ministry of Transport, during from 1986 to 1993. 'Hyogo eq.' represents the data obtained during the 1995 Hyogo-ken nambu Earthquake. 'K-net' represents the data obtained by the National Research Institute for Earth Science and Disaster Prevention.

2.2. Prediction Model For Given Magnitude And Distance (Model-I)

Simulation of ground motion by evolutionary process Based on the 118 components of modified rock surface motion explained above, the earthquake motion prediction model for given earthquake magnitude and hypo-central distance has been proposed.

Earthquake acceleration with nonstationary frequency content can be represented by Eqn.1;

$$x(t) = \sum_{k=1}^{m} \sqrt{4\pi \cdot G_x(t, 2\pi f_k)\Delta f} \cdot \cos(2\pi f_k t + \phi_k) \tag{1}$$

in which $\sqrt{G_x(t, 2\pi f_k)}$ is evolutionary power spectrum (Kameda, 1975) for time t and frequency f_k, ϕ_k is independent random phase angles distributed over $0 \sim 2\pi$, and m is the number of superposed harmonic components.

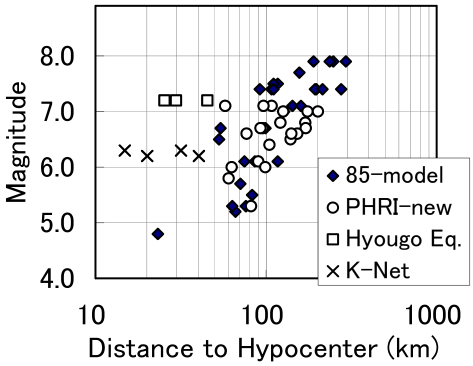

Fig.1 The relationship with Magnitude and Distance to hypocenter in the dataset of 118 components

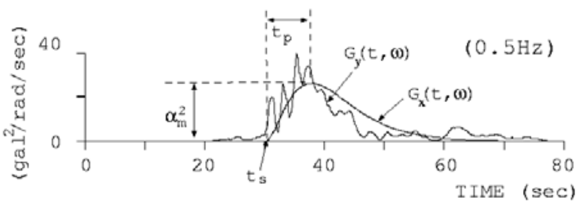

Fig.2 Evolutionary Power Spectrum

The upper and lower boundary frequencies, fu , fl , are fixed as fu =10.03 Hz, fl =0.13 Hz, and also m and Δf are fixed as m =166 and Δf =0.06 Hz.

The following time-varying function is adopted for the model of $\sqrt{G_x(t,2\pi f_k)}$,

$$\sqrt{G_x(t,2\pi f)} = \begin{cases} 0 & (0 \le t \le t_s) \\ \alpha_m(f)\dfrac{t-t_s(f)}{t_p(f)}\exp\left[1-\dfrac{t-t_s(f)}{t_p(f)}\right] & (t_s < t) \end{cases} \quad (2)$$

in which $t_s(f)$ and $t_p(f)$ is starting time and duration parameter, respectively, and $\alpha_m(f)$ is intensity parameter which represents the peak value of $\sqrt{G_x(t,2\pi f_k)}$. These parameters have been determined relative to recorded acceleration time histories (Kameda, et. al., 1980). Fig.2 shows example of recorded and modeled evolutionary spectra.

The regression equations listed in Table 1 are used for the model parameters to establish the prediction model for given magnitude and distance. The coefficients for the model parameters in Eqn.(3), (5), and (7) have some typical inclination on the frequency axis, they were modeled as a function of frequency using the least square method.

Table 1 Estimation formulas for model parameters and correction factors

$\log \alpha_m(f) = B_0(f) + B_1(f)\cdot M - B_2(f)\cdot \log R$	(3)	$B_0(f) = -0.657 + 1.637\cdot\log f - 1.642\cdot(\log f)^2$ $B_1(f) = 0.562 - 0.208\cdot\log f + 0.0918\cdot(\log f)^2$ $B_2(f) = 1.335 - 0.115\cdot\log f - 0.443\cdot(\log f)^2$	(4)
$\log t_p(f) = P_0(f) + P_1(f)\cdot M + P_2(f)\cdot\log R$	(5)	$P_0(f) = -0.808 - 0.929\cdot\log f$ $P_1(f) = 0.123 + 0.134\cdot\log f$ $P_2(f) = 0.357 - 0.083\cdot\log f$	(6)
$t_s'(f) = t_s(f) - t_m = S_1(f)\cdot R$	(7)	$S_0(f) = 0.0$ (fixed) $S_1(f) = (0.863 - 0.509\cdot\log f - 1.141\cdot(\log f)^2)\times 10^{-2}$	(8)
$N_G = 8.71\times 10^{-11}\cdot M_0^{0.409}$			(11)
$\log \beta_0(f) = d_0(f) + d_1(f)\cdot\log M_0$	(13)	$d_0(f) = -0.449 + 0.641\cdot\log f + 0.178\cdot(\log f)^2$ $d_1(f) = 0.0157 - 0.0306\cdot\log f$	(14)

2.3. Prediction Model For Given Fault Parameters (Model-II) based on superposing evolutionary power spectra from small earthquake event

It is known that the past strong motion records obtained from great earthquakes show the effect of rupture direction relative to sites and geometrical condition between sites and fault on ground motion intensities and their duration. In the case that these physical fault parameters in addition to the earthquake magnitude are given for the ground motion prediction, to incorporate these parameters effectively is important in the engineering subjects. Herein the basic prediction model obtained in the former section is extended into the model that incorporates a size of fault, fault rupture direction and its velocity, and seismic moment as a parameter of earthquake scale.

Fig.3 gives general concept of the model. A fault is divided into a number of small events that correspond to the unit event of magnitude M=6.0 in the Model-I. In this extended model, the arriving time lag resulted from rupture on the fault and differences of propagation distance of ground motions for each individual unit event are considered. Consequently, the evolutionary power spectra for great earthquakes are given from the superposition of those from each unit event on the time domain.

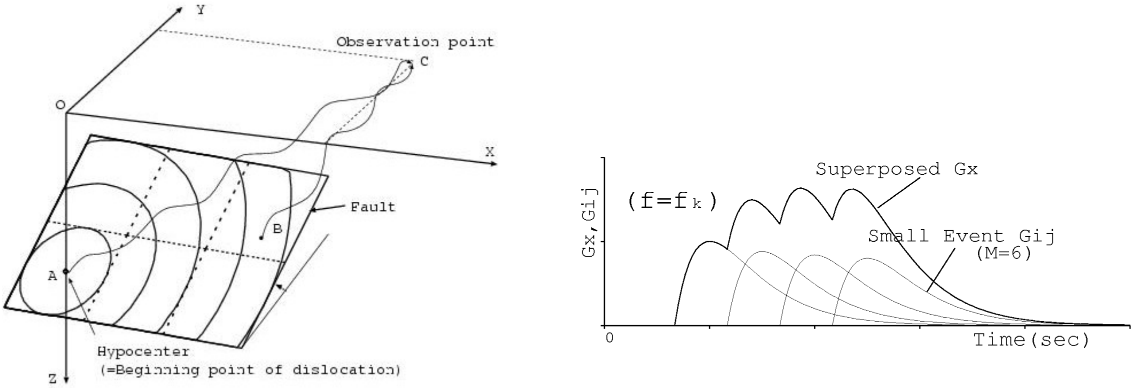

Fig.3 Fault modeling with multiple fault rupture and Superposed evolutionary power spectra

The number of superposition, N_G, of evolutionary spectra is defined. The parameter, N_G, represents number of small unit events on a specific great fault. The following procedure has been performed to obtain the superposition parameter. The magnification factor, $c(f)$, defined by Eqn.(9) can be used for amplification value of evolutionary power spectrum.

$$c(f) = \int_0^{t_0} \sqrt{G_x(t,2\pi f)}dt \Big/ \int_0^{t_0} \sqrt{G^*_{ij}(t,2\pi f)}dt \qquad (9)$$

where $\sqrt{G_x(t,2\pi f_k)}$ is simulated evolutionary spectrum for the specific data, $\sqrt{G^*_{ij}(t,2\pi f_k)}$ is evolutionary spectrum given from the Model-I which corresponds to the earthquake magnitude M=6.0 and the same hypo-central distance of the specific data, and t_0 is duration of the record. The number of superposition, N_G, the average of the magnification factor, $c(f)$, along the logarithmic frequency axis is defined as,

$$N_G = \int_{\log f_1}^{\log t_2} c(f) d(\log f) dt / (\log f_1 - \log f_2) \qquad (10)$$

where the lower and upper frequencies f1, f2 are fixed as f1 =0.13 Hz and f2 =10.03 Hz. The parameter, N_G, has been obtained for 118 components of acceleration time histories. The parameter, N_G, has been scaled for M_0, and the relation has been obtained as Eqn.(11) in the Table 1.

The superposed evolutionary spectra for great earthquake is given by

$$\sqrt{G_{x0}(t,2\pi f)} = \frac{N_G \cdot \beta(f)}{N_x \cdot N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \sqrt{G_{ij}(t,2\pi f)} \qquad (12)$$

where G_{ij} is evolutionary spectrum for each unit event e_{ij} corresponding to the earthquake magnitude M=6.0 and hypo-central distance R_{ij} in the Model-I, and the suffix, i and j, represent the position of each event on the fault. N_x and N_y represent the number of unit event in the direction of fault width and length.

The number of superposition, N_G, is generally not an integral number, therefore the term $N_x \cdot N_y$ is necessary to keep the superposed power correctly. Further the correction factor $\beta(f, M_0)$ in Eqn.(13) is incorporated for superposing of each frequency component, since the number of superposing of evolutionary spectra depends on the frequency. This correction factor, $\beta(f, M_0)$, has been obtained from the regression analysis of the parameter, $c(f)$, defined by Eqn.(9) on seismic moment. The estimation formula for the correction factor, $\beta(f, M_0)$, is given in Table 1.

3. THE COMPARISON OF THE EARTHQUAKE MOTION CHARACTERISTIC CONSIDERING A NUMBER OF THE SUPERPOSITION OF THE EVOLUTIONARY POWER SPECTRUM

It is thought that the large-scale dislocation destruction in the focal region is superposition of some small-scale event of destruction. Therefore, the strong earthquake motion in the focal region can be given by superposing the each evolutionary power spectra from unit event on a time axis, considering a delay in arrival time of the earthquake wave from an expanse of the fault, a rupture velocity and its direction on the fault.

Here, the ratio of the power (NG; the number of the superposition) of the evolutionary power spectrum from several typical earthquake records obtained recently in Japan and that from statistical mean value of past earthquake records which is equivalent to M=6 is derived every frequency in the range of 0.1~10.0Hz, and the characteristics of each earthquake motion are considered. In addition, the evolutionary power spectrum which is equivalent to M =6 is estimated by EMPR MODEL-I, (in the former section), which is provided by a multiple regression analysis for magnitude (M) and focal distance (R) from the database which consists 118 components of the main severe earthquake records in Japan.

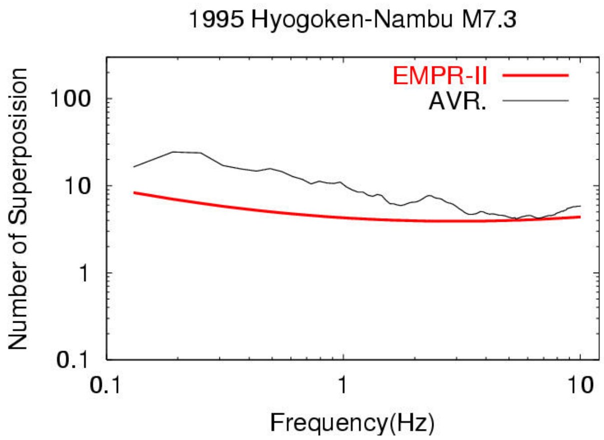

Fig.4(a) 1995Hyogoken-Nambu Earthquake

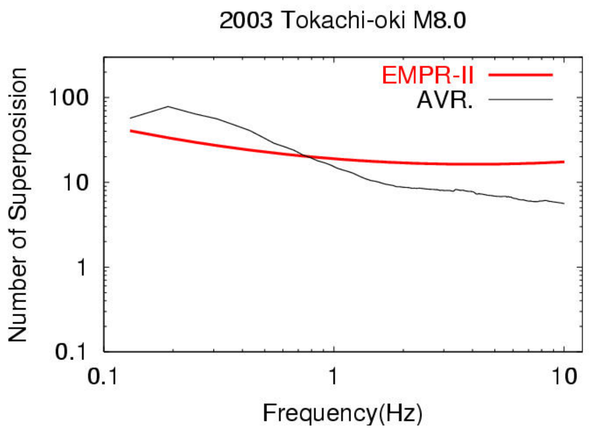

Fig.4(b) 2003Tokachi-Oki Earthquake

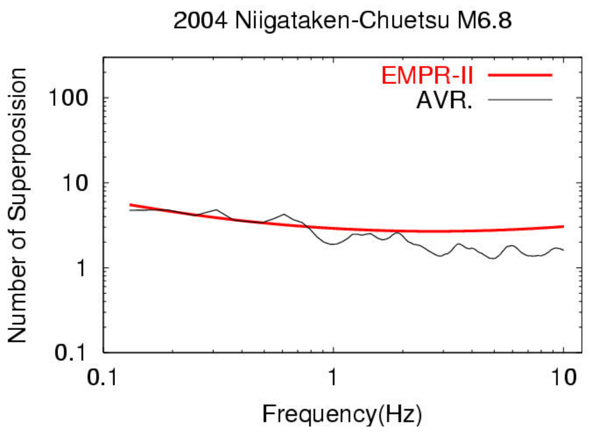

Fig.4(c) 2004 Niigataken-Chuetsu Earthquake

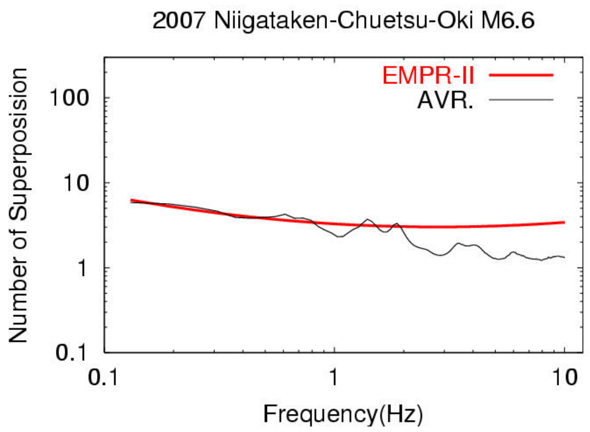

Fig.4(d) 2004 Niigataken-Chuetsu-Oki Earthquake

Fig.4 Distribution of Number of Superposition for Recent Earthquake in Japan

Fig.4 shows the ratio of the power (NG; the number of the superposition) of the evolutionary power spectrum from recent earthquake records obtained by KiK-net. Black lines in the figures (shown in figures; AVR.) represent the mean value of the power spectra exceed 4 in seismic intensity scale on the free rock basement, and red lines (shown in figures; EMPR-II) represent statistical expectation of the power spectra equivalent to seismic moment.

Compared with the Back and the Red lines, in all earthquakes commonly, the power is tend to be high in the low frequency range and low in the high frequency range. Especially, at the 2003 Tokachi-oki earthquake (Fig.4(b)) the power declines remarkably in the high frequency range.

In addition, at the 1995 Hyogoken-nambu earthquake (Fig.4(a)), the power exceeds the statistical expectation and the trend is remarkable in the low frequency range. The other hand, at the 2004 Niigataken-Chuetsu earthquake (Fig.4(c)), the power is almost equal to the statistical expectation except it tends to decline slightly in the high frequency range. At the 2007 Niigataken-Chuetsu-oki earthquake (Fig.4(d)) indicate a similar tendency to the 2004 Niigataken-Chuetsu earthquake relatively.

4. THE SIMULATION OF THE EARTHQUAKE MOTION CONSIDERING THE SPECTRUM CHARACTERISTIC OF THE OBSERVATION RECORD

4.1 The number of superposition considering the spectrum characteristic of the observation record

As the case of the investigating the damage of structure during past earthquake, when the observation records equivalent to that on free rock surface can be obtained at near the hypo-central region, the past earthquake motion could be estimated considering the spectral characteristics of the strong motions.

Herein, instead of $N_G \cdot \beta(f)$ in Eqn.(11), by using the follow equation, the number of superposition based on the spectral characteristics of the specific earthquake motion could be determined.

$$A_p(f) = \frac{\alpha'_m(f) \cdot t'_p(f)}{\overline{\alpha_m}(f) \cdot \overline{t_p}(f)} \tag{15}$$

Where, $\overline{\alpha_m}(f)$ and $\overline{t_p}(f)$ are given from the EMPR (Model-I) which corresponds to the earthquake magnitude M=6.0 and the same hypo-central distance of the specific data, $\alpha'_m(f)$ and $t'_p(f)$ are given from the free rock surface wave motion corresponds to the observed record.

Then, the Eqn.(11) should be redefined as follows;

$$\sqrt{G_{x0}(t,2\pi f)} = \frac{A_p(f)}{N_x \cdot N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \sqrt{G_{ij}(t,2\pi f)} \tag{16}$$

4.2 The case study of the earthquake simulation by the presented technique

The case study of the earthquake simulation at the site of damaged structure considering the spectral characteristics of the recorded strong motions is performed. Table 2 shows the free rock surface motion corresponds to earthquake records. In this case, 13 observation points are selected. By using horizontal NS and EW components, the spectral intensity of the earthquake is calculated. Fig.6 shows simulated earthquake time-histories, response spectra and Fourier spectrum.

Table 2. Earthquake Records by KiK-net during
2007 Niigataken-chetsu-oki earthquake (2007.7.16)

ID	LOCATION	LAT.	LON.	Hypocentral Distance	Peak Accel. (gal)		
					EW	NS	UD
NIGH02	ASAHI	38.28	139.55	116.45	48.38	26.23	22.78
NIGH03	ARAKAWA	38.13	139.43	97.89	−23.99	28.15	−8.82
NIGH04	SEKIKAWA	38.13	139.55	105.38	−59.67	−60.65	26.98
NIGH05	SEIROU	37.97	139.28	77.04	−69.26	75.47	−12.49
NIGH06	KAMO	37.65	139.07	45.16	−148.38	−149.20	−88.60
NIGH07	MURAMATSU	37.66	139.26	61.16	−66.59	−72.38	−20.67
NIGH09	SHITADA	37.54	139.13	48.90	−123.47	121.83	49.25
NIGH11	KAWANISHI	37.17	138.75	47.50	124.11	161.31	51.02
NIGH13	MAKI	37.05	138.40	61.32	−165.90	261.25	−66.91
NIGH16	ITOIGAWA	36.93	137.85	97.77	72.78	49.01	−24.01
NIGH17	MYOKO-KOGEN	36.85	138.10	91.65	−17.89	−25.51	−11.05
NIGH18	MYOUKOU	36.94	138.26	76.87	−95.87	−94.96	−26.34
NIGH19	YUZAWA	36.81	138.79	86.04	−47.57	−131.13	23.28

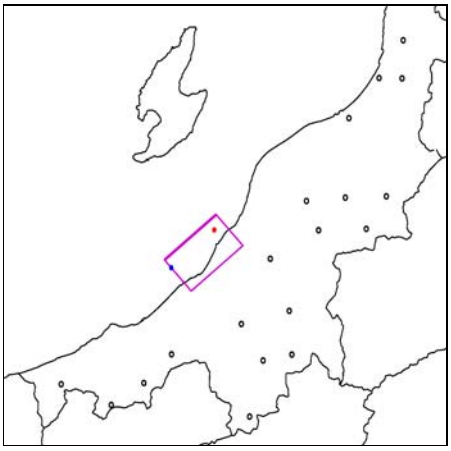

Fig.5 Distribution of KiK-net Station
(The rectangle in the figure shows
hypo-central region)

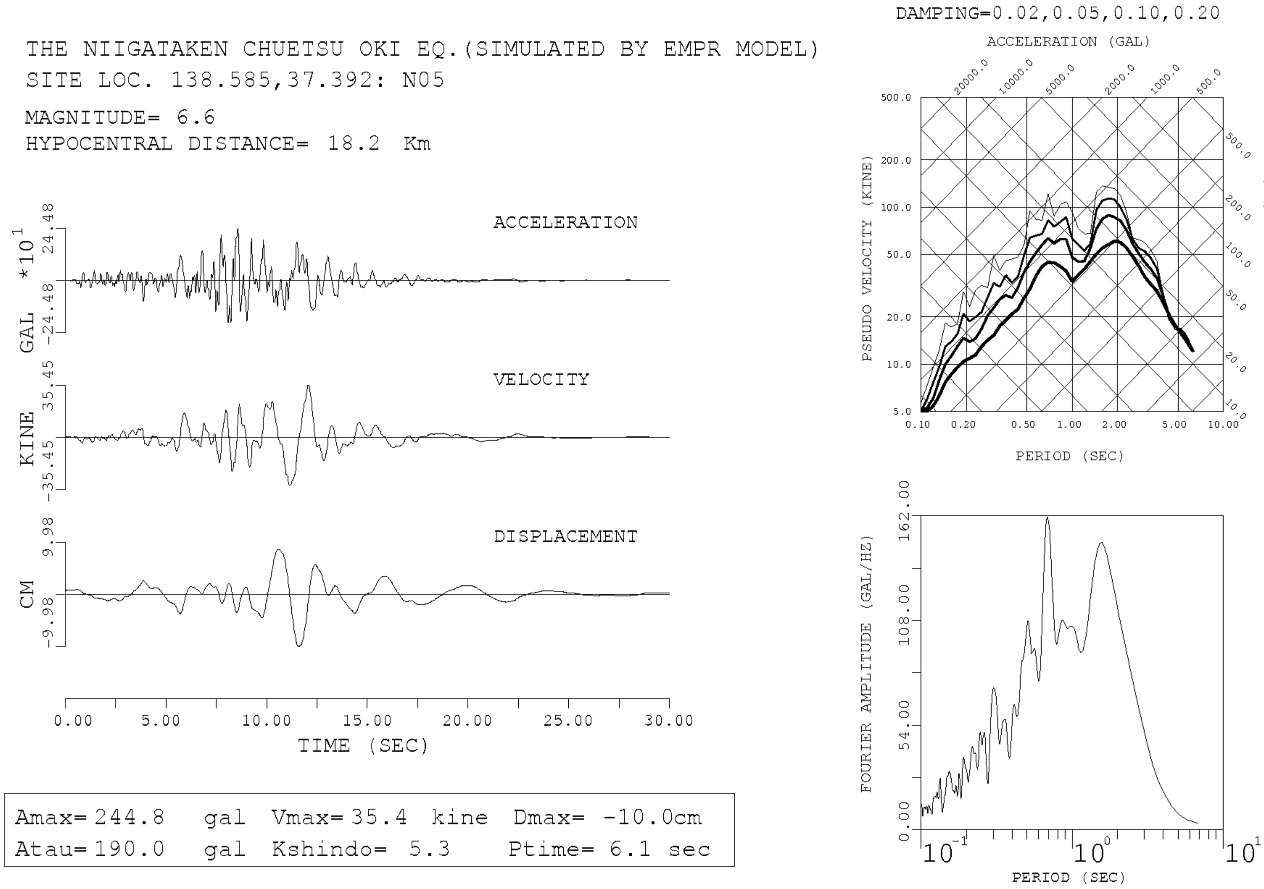

Fig.6 Estimated earthquake motion on free rock surface at the site of the Lon. 138.585E, Lat.37.392
during 2007 Niigataken Chuetsu-oki earthquake

CONCLUSIONS

1. With an analysis of observed earthquake record, a simulation procedure is presented for estimating strong ground motions at any site during past earthquakes.

2. The general scheme of strong motion prediction model by superposing the evolutionally power spectra from small earthquake event are presented.

3. Strong motion data used in the tequnique consists of 118 components of acceleration time histories that have been obtained at 25 stations during 37 Japanese earthquakes. The modified equivalent linearization method for the response analysis of layered ground has been applied to obtain on free rock surface motions from observed records.

4. On the basis of the dataset, two types of prediction models are presented: the EMPR Model-I for given earthquake magnitude and hypo-central distance, and the Model-II for given fault parameters, such as fault length and width, seismic moment of fault, rupture pattern and rupture velocity, and propagation velocity of seismic waves. The EMPR Model-II incorporates the effect fault size, successive fault rupture, and rupture direction, on characteristics of ground motion. In the Model-II, the evolutionary power spectrum from large earthquake is calculated by superposing those from unit event which corresponds to the earthquake of M=6.0 in the Model-I.

5. The number of superposition of evolutionary spectra is presented. The parameter represents number of small unit events on a specific great fault. This depends on the frequency and scaled in terms of seismic moment, the parameter has been obtained from the regression analysis by using 118 earthquake dataset.

6. The comparison of the characteristic of recent earthquake motion in Japan considering the number of superposition of the evolutionary power spectrum is performed.

7. The number of superposition considering the spectrum characteristic of the observed record is redefined. It is given from both he EMPR (Model-I) that corresponds to the earthquake magnitude M=6.0 and the same hypo-central distance of the specific data and the free rock surface wave motion corresponds to the observed record obtained at near the hypo-central region.

8. The redefined number of superposition parameter are incorporated into the strong motion prediction model, which can simulate the non-stationary time-history on the rock surface by superposition of the evolutionary power spectra with the given fault parameters, such as the fault length and the width, the seismic moment, the rupture pattern of the fault and propagation velocity of seismic waves.

9. A case study of the earthquake simulation by the presented technique is performed. Some simulations of eathquake motion during 2007 Niigataken Chuetsu-oki earthquake are presented for the purpose of investigating the structure damage.

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