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THE INFLUENCE OF FAULT PLANE IRREGULARITIES ON STRONG GROUND MOTIONS

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SUMMARY

A semi-empirical method has been developed to estimate strong ground motions, which takes into account fault plane irregularities. SD was newly introduced as a parameter showing the degree of the variation of displacement on the fault plane. The new method was applied to synthesis of strong ground motions at 14 stations during 6 large earthquakes with magnitude M of 6.7 to 7.9 occuring in and around Japan. The synthesized records were in good agreement with the observed ones, if SD was chosen to be about 1.0. The rms value $\sqrt{E(\tau^2)}$ of stress drop over the fault plane can be estimated from SD and the global stress drop $\Delta\sigma$. $\sqrt{E(\tau^2)}$ is about 1.4 times as large as $\Delta\sigma$ for SD=1.0.

INTRODUCTION

Higher frequency strong ground motions are too complicated to simulate by a deterministic model, because of the sensitivity of high frequency waves to the details of fault plane irregularities. To avoid the difficulty regarding the fault plane irregularities, stochastic models specified by a small number of statistical parameters have been proposed. (e.g., Hirasawa(Ref.1); Izutani(Ref.2); Koyama(Ref.3); Papageorgiou and Aki(Ref.4)) Their results indicated that the fault plane irregularity is an important factor to the excitation of high frequency waves, while the excitation of low frequency waves can be described by the average displacement or the average stress drop over the fault plane. To estimate strong ground motions over a wide frequency range, therefore, a hybrid of deterministic and stochastic models is effective, in which gross features of rupture propagation are specified deterministically, but the details of the process are described by the stochastic model.

Takemura and Ikeura(Ref.5) proposed a semi-empirical method for estimating strong ground motions over a wide frequency range with the assumption of a hybrid deterministic and stochastic fault models. The deterministic model is based on the kinematic source model of Haskell and the similarity law of earthquakes, which are the same assumptions adopted by Irikura(Ref.6). The stochastic model is described by a specific distribution function of displacement on the fault plane. Takemura and Ikeura(Ref.5) simulated strong ground motions during some large earthquakes in and around Japan using the semi-empirical method. In this paper, the theoretical basis of the method by Takemura and Ikeura(Ref.5) will be discussed and the influence of fault plane irregularities on strong ground motions will be estimated quantitatively based on the results of the simulation of strong ground motions.

THEORETICAL BASIS OF THE METHOD

According to Takemura and Ikeura(Ref.5), the displacement on the fault plane of large earthquake was divided into two parts. One is the average displacement Do over the fault plane and the other is the deviation ΔDij from the average. A seismic wave SL(t) due to the average displacement Do and a seismic wave Ss(t) due to the deviation ΔDij from Do were derived as follows:

$$SL(t)= \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}(Re/Rij)Se(t-\tau_{ijk}) \quad (1)$$

$$Ss(t)= \sum_{i=1}^{n}\sum_{j=1}^{n}\kappa_{ij}(Re/Rij)Se(t-\tau_{ij1}) \quad (2)$$

where Re is the source to site distance of element earthquake, Rij is the distance from each segment on the fault plane to the site, τijk is the total delay time due to the fault slip, the rupture propagation, and the travel time of seismic waves, Se(t) is the observed seismograms of the element earthquake, and n is a scaling parameter which is obtained from the cube root of seismic-moment ratio between the large and the element earthquakes and gives the number of irregularities on the fault plane. κ_{ij} was newly introduced as a probabilistic parameter of the normal distribution with the average of 0 and with the standard deviation of SD. The final result of synthesized strong ground motion Ssyn(t) can be expressed as a sum of SL(t) and Ss(t).

We try to calculate the expected value of the square of the Fourier spectrum for the synthesized wave Ssyn(t). For example, in the case of the bi-directional rupture propagation, the expected value can be easily derived by the method of Boore and Joyner(Ref.7) as follows:

$$E\left[|Fsyn(\omega)|^2\right]=|FL(\omega)|^2+n^2SD^2|Fe(\omega)|^2\left(1-\left(\frac{\sin\frac{\omega TL}{2}}{\frac{\omega TL}{2}}\right)^2\left(\frac{\sin\frac{\omega Tw}{2}}{\frac{\omega Tw}{2}}\right)^2\right) \quad (3)$$

where FL(ω) and Fe(ω) are the Fourier spectra of SL(t) and Se(t), and TL and Tw are apparent times of rupture propagation along the fault length L and fault width W, which are defined as follows:

$$TL=L/VR\ \cos\theta \quad (4)$$

$$Tw=W/VR\ \sin\theta \quad (5)$$

where VR and θ show rupture velocity and the direction of rupture propagation from the direction of the fault length. It is found that the second term in equation (3) becomes zero at zero frequency. Therefore, the long period component of seismic waves can be described by FL(ω), which is due to the average displacement over the fault plane. On the other hand, in high frequency range, the second term has an effective value, which is determined exactly by the number of irregularities n^2, the variation of displacement SD, and the spectrum of the element event Fe(ω), irrespectively of the direction of rupture propagation. This indicates that the high frequency seismic radiation is not affected by the effect of the seismic directivity.

SYNTHESIS OF STRONG GROUND MOTIONS

Table 1 shows earthquakes and observation stations for simulated strong motion records. M and Me are the magnitude of large and element earthquakes in JMA(Japan Meteorological Agency)scale. Stations with a star and with double stars provided us with displacement records and velocity records, respectively. Sato et al.(Ref.8) simulated strong motion records from the 1980 Izu-toho-oki earthquake by using various different methods and their results were compared. The method by Takemura and Ikeura(Ref.5) was also used. In this paper, we will adopt the results in the study of Sato et al.,(Ref.8) partain to the Izu-toho-oki event. Fault parameters used for the simulations were based on some other studies(Ref.5).

The element earthquakes, which are summarized in Table 1, are selected for the simulations based on the relation between magnitude M and fault patch area ΔS for the large earthquakes. Fig.1 shows the relation between M and ΔS, which is summarized based on the results of Aki(Ref.9),Izutani(Ref.2) and Sato(Ref.10). Aki(Ref.9) estimated barrier intervals from the average length of fault segments observed by geologists on the earth's surface after large earthquakes. These values are consistent with the barrier intervals obtained from acceleration power spectra using the specific barrier model (Ref.9). Sato(Ref.10) estimated the barrier intervals for the 1983 Nihonkai-chubu earthquake by using the specific barrier model. Izutani(Ref.2) obtained the second corner frequency fc* through the analysis of accelerograms for some Japanese earthquakes. According to Koyama(Ref.3), fc* is inversely proportional to the average fault patch size. We calculated the fault patch areas from the barrier intervals by Aki(Ref.9) and Sato(Ref.10) and from fc*'s by Izutani(Ref.2) on the assumption of a circular fault patch. The magnitude scale adopted in Fig.1 is JMA magnitude or surface-wave magnitude. The fault areas Se of element earthquakes are also plotted in Fig.1, which are estimated from magnitude using the relation between M and Se (Ref.11) It is found in Fig.1 that ΔS increases with M, though the relation between ΔS and M cannot be accurately determined because of the large scattering of the data. We can also find that the fault area Se of selected element earthquakes are included within the distribution of the data of ΔS.

Seismic moment Mo, scaling parameter n, and the value of SD used for estimating strong ground motions are summarized in Table 2. The seismic moment Mo and the global stress drop for each event are obtained from some other studies (Ref.5). The value of SD is determined so as to match the spectral amplitude of the synthesized record with that of the observed one in the period range shorter than 1s. We can find that the value of SD ranges from 0.7 to 1.5 irrespective of the magnitude and the seismic moment of the large earthquake.

Fig.2 shows observed and synthesized accelerograms at Miyako of the 1978 Miyagi-oki earthquake. Fig.3 shows the locations of Miyako station ,epicenter of the element event, and the fault plane of the 1978 Miyagi-oki event. It is found in Fig.2 that the amplitude of Ss(t) is much larger than that of SL(t). This indicates that the heterogeneity of faulting is an important factor to the generation of high frequency waves. Fig.4 shows response spectra with damping coefficient h=0.05 of observed and synthesized records. The amplitude of Ss(t) is almost equal to that of SL(t) at about 1.5 s, while Ss(t) is about 5 times as large as SL(t) in the period range shorter than 0.5 s. We can easily guess that SL(t) becomes larger than Ss(t) at longer periods, since the sum of the seismic moments for Ss(t) waves is 0 over the fault plane. The spectrum of the synthesized record is in good agreement with that of the observed one. The results of the simulations for the other earthquakes were presented in the paper by Takemura and Ikeura(Ref.5). The spectrum obtained by the simulation provided us with satisfactory agreement and the amplitude of Ss(t) waves is much larger than SL(t) in high frequency range for each event.

DISCUSSIONS

The semi-empirical method proposed here must face two problems for predicting strong ground motions due to disastrous earthquakes. The first problem is how to determine the magnitude of the element earthquake selected for the synthesis. The present method requires that the size of fault area of the element event should be consistent with the fault patch size on the fault plane of the large earthquake. According to the equation (3), wave amplitudes of high frequency component are determined by n, SD, $Fe(\omega)$. n and $Fe(\omega)$ depend on the size of the element event. However, we can easily derive that $n|Fe(\omega)|$ is constant irrespectively of the size of element earthquake in the frequency range higher than the corner frequency of the element earthquake under the assumption that the source spectrum of the element event satisfies the ω^{-2} model. Therefore, the first problem is not so important to predict the high frequency component of strong ground motion. On the other hand, in the case of the evaluation of strong ground motions in wide frequency range including the corner frequency of the element earthquake, the size of the selected element event influences on the results of the evaluations. It is an important future problem to elucidate the relation between the fault patch area and the size of large earthquakes for evaluating strong ground motions in the wide frequency range.

The second problem is how to determine the value of SD. To resolve this problem, we have to discuss the physical meaning of SD in relation to the stochastic source model. Hirasawa(Ref.1) and Izutani (Ref.2) proposed a stochastic source model in the high frequency range. According to this model, the acceleration due to S-waves radiated from a large number of element faults consisting of a circular fault of an earthquake can be approximated by a random pulse sequence. The power spectral density of an acceleration is proportional to the root-mean-square (rms) of stress drop $\sqrt{E(\tau^2)}$, which is a determinant factor of amplitudes of high frequency waves. We assume that the average stress drop $E(\tau_{ij})$ of element faults is equal to global stress drop $\Delta\sigma$. Based on the similarity law of earthquakes, the global stress drop $\Delta\sigma$ can be written using the displacement De of the element earthquake as follows:

$$\Delta\sigma = C De / \Delta L \tag{6}$$

where C is a constant determined by elastic constants and ΔL is a characteristic length of the element earthquake which is consistent with the fault patch size on the fault plane. Based on the assumption that $E(\tau_{ij}) = \Delta\sigma$ and relation (6), a stress drop τ_{ij} of each element fault can be given as,

$$\tau_{ij} = \Delta\sigma(1+\kappa_{ij}) \tag{7}$$

where κ_{ij} is the ratio of the deviation ΔDij from the average displacement Do to the displacement De of the element earthquake. Since $E(\kappa_{ij})=0$ and $\sqrt{E(\kappa_{ij}^2)}=SD$, the rms stress drop $\sqrt{E(\tau^2)}$ can be easily obtained from equation (7) as follows:

$$\sqrt{E(\tau^2)} = \Delta\sigma\sqrt{1+SD^2} \tag{8}$$

The value of SD and the global stress drop $\Delta\sigma$ obtained for each earthquake are summarized in Table 2. Hirasawa(Ref.1), Izutani (Ref.12) and Sato(Ref.10) estimated the rms stress drops $\sqrt{E(\tau^2)}$ from peak acceleration and power spectral density of observed accelerograms for some earthquakes. We find that rms stress drop $\sqrt{E(\tau^2)}^*$ calculated from SD and $\Delta\sigma$ are consistent with $\sqrt{E(\tau^2)}$ from observed accelerograms. This result indicates the validity of equation (8). According to Table 2, SD value shows of 0.7 to 1.5 for 6 events, while $\Delta\sigma$ ranges from 32 to 130 bar. These results suggest that the value of SD may be fixed to the average value SD=1.0 for predicting strong ground motions, because the variation of rms stress drop is mainly due to $\Delta\sigma$. Then, $\sqrt{E(\tau^2)}$ is about 1.4 times as large as $\Delta\sigma$.

CONCLUSIONS

The theoretical basis of the semi-empirical method proposed by Takemura and Ikeura(Ref.5) is discussed and the influence of the fault plane irregularities on strong ground motions is estimated quantitatively based on the results of the simulations of strong ground motions. The results obtained can be summarized as follows:

(1) The amplitude of Ss(t) waves due to the deviation ΔDij from the average displacement Do over the fault plane is much larger than that of SL(t) waves due to Do in the high frequency range. This indicates that fault plane irregularity is an important factor in the excitation of high frequency waves.
(2) The seismic radiation due to the irregularities of displacement on the fault

plane is not affected by the effect of the seismic directivity.
(3) The value of SD describes the degree of heterogeneity of the displacement on the fault plane. SD values are obtained from 0.7 to 1.5 for 6 earthquakes. According to Hirasawa(Ref.1) and Izutani(Ref.2), peak acceleration and power spectral density of acceleration is proportional to the rms stress drop $\sqrt{E(\tau^2)}$ of the element faults on the fault plane. The relation among $\sqrt{E(\tau^2)}$, SD and global stress drop $\Delta\sigma$ can be derived based on the assumption of the similarity law of earthquakes. The variation of SD is relatively small comparing with that of $\Delta\sigma$. Therefore, SD value may be fixed to the average SD=1.0 provisionally for predicting strong ground motions during large earthquakes. Then, $\sqrt{E(\tau^2)}$ is about 1.4 times as large as $\Delta\sigma$

Table 1 Observation Stations and Magnitude for Large and Element Earthquakes.

Event	Station	M	Element Date(JST)	Me
1968 Tokachi-oki	Hachinohe	7.9	Dec. 2,1981	6.2
1983 Nihonkai-chubu	Akita, Furofushi Hachinohe *, Sendai* Tokyo *	7.7	June 9,1983	6.1
1973 Nemuro-oki	Kushiro	7.4	Sep. 20,1974	5.5
1978 Miyagi-oki	Miyako,	7.4	June 8,1977	5.8
1978 Oshima-kinkai	Shimizu-miho	7.0	Jan. 14,1978	5.1
1980 Izu-toho-oki (Sato et al.,1988)	Kawana Shuzenji Nebukawa Tateyama Omaezaki **	6.7	June 28,1980	4.9

* Displacement records ** Velocity records

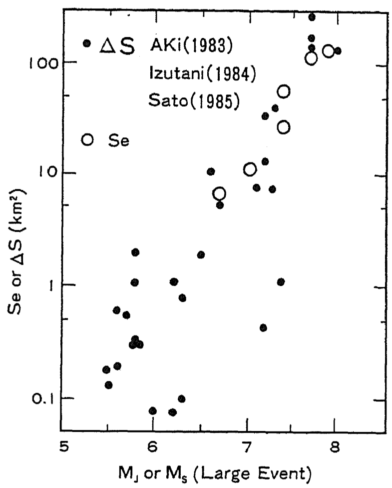

Fig.1 A Relation between Fault Patch Area ΔS (or Fault Area Se of Element Earthquake) and Magnitude M of Large Earthquake.

Table 2 Source Parameters for Estimating Strong Ground Motions.

Event	Mo(dyne・cm)	n	S_D	$\Delta\sigma$(bar)	$\sqrt{E(\tau^2)}$*(bar)	$\sqrt{E(\tau^2)}$(bar)
Tokachio-oki	2.8×10^{28}	10	0.8	32	41	48
Nihonkai-chubu	5.0×10^{27}	8	1.3	130	210	360
Nemuro-oki	6.7×10^{27}	13	1.5	35	63	—
Miyagi-oki	3.1×10^{27}	7	1.0	70	99	120
Oshima-kinkai	1.1×10^{26}	5	0.7	41	50	—
Izu-toho-oki (Sato et al.1988)	4.4×10^{25}	6	1.0	—	—	—

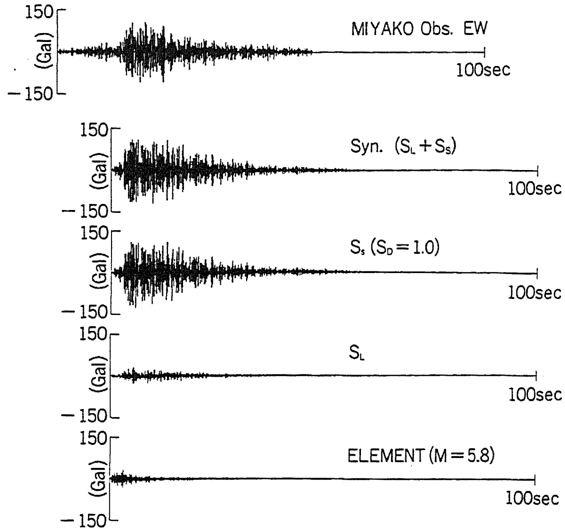

Fig.2 Observed and Synthesized Accelerograms in EW Component at Miyako for the 1978 Miyagi-oki Earthquake.

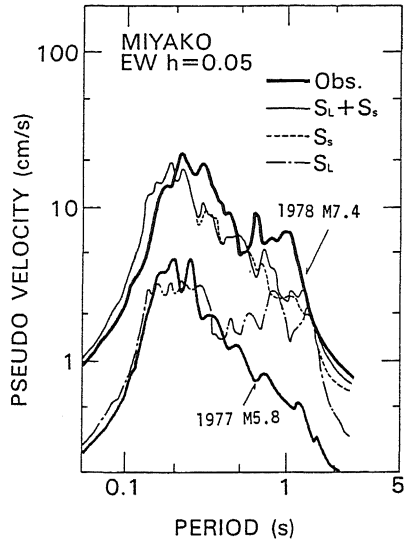

Fig.4 Response Spectra (h=0.05) of Observed and Synthesized Accelerograms in EW Component at Miyako.

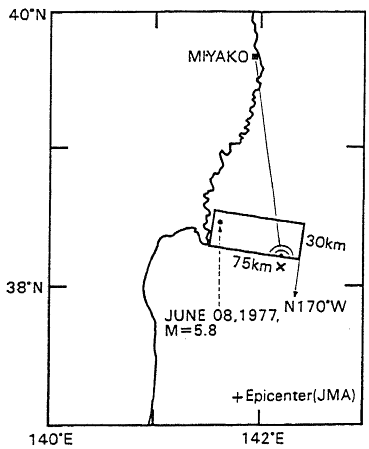

Fig.3 Locations of Fault Plane of the 1978 Miyagi-oki Earthquake, the Epicenter of the Element Event, and the Miyako Station.

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