MODELING OF HIGH-FREQUENCY WAVE RADIATION PROCESS ON THE FAULT PLANE FROM THE ENVELOPE FITTING OF ACCELERATION RECORDS

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SUMMARY

High-frequency (higher than 1 Hz) wave radiation processes are estimated for the 1993 Kushiro-oki, Japan, earthquake (Mw = 7.6) and the 1995 Hyogo-ken Nanbu, Japan, earthquake (Mw = 6.9) from the envelope inversion of strong ground motion acceleration seismograms. For the 1993 Kushiro-oki earthquake, high-frequency (2 - 10 Hz) waves are little radiated around rupture starting point but radiated mainly near the periphery of the fault plane, while low-frequency waves are mainly radiated from rupture starting point. For the 1995 Hyogo-ken Nanbu earthquake, both high- (2 - 10 Hz) and low-frequency waves are radiated from the part where the surface break appeared (Nojima fault). High-frequency waves are also radiated from the discontinuity of the fault planes seen at the Akashi strait. The result of the 1993 Kushiro-oki earthquake can be interpreted with crack model. This indicates the rupture process of this event is rather simple. On the contrary, the rupture process of the Hyogo-ken Nanbu earthquake are more complicated. The fault plane discontinuity is interpreted to have behaved as a geometrical barrier and generate high-frequency waves when ruptured. This kind of analysis will play an important role for the modeling of rupture process for frequencies higher than 1 Hz, which are required for realistic strong ground motion prediction, considering conventional waveform inversion is not applicable to such high frequencies.

INTRODUCTION

Owing to the remarkable progress both in observation systems and in analysis methods, we have been able to obtain a great deal of knowledge about the source process of earthquake. In the 1980's, the inversion technique was successfully introduced to the estimation of detailed source processes. Particularly, the usage of near field data made it possible to determine the rupture processes of earthquakes with high accuracy and resolution.

However, the frequency coverage of source process study by the analysis of seismic waveforms has been limited up to about 1 Hz. From the viewpoint of disaster prevention, it is very important to know from what part of the fault plane seismic waves higher than 1 Hz are radiated, because those frequencies have a strong effect on common structures. Accumulation of this kind of knowledge will be a very important database for the modeling of source process for the realization of the practical strong ground motion prediction. At the same time, analysis of higher-frequency waves is indispensable to obtain further understanding of the dynamics of earthquake rupture process. This is easily understood by recalling that the heterogeneity or irregularity of rupture process generates the complexity of observed waveforms.

It is very difficult to do a source inversion for seismic waveforms whose frequencies are higher than 1 Hz due to two problems. One is the difficulty in obtaining Green's functions accurate enough for such high frequencies, and the other is that in doing a waveform inversion for such oscillatory data. The latter can be overcome by a simple idea of using envelopes instead of waveforms as inversion data. Recently, this approach has been adopted by some researchers for the estimation of high-frequency radiation process on the fault plane (e.g. Zeng *et al.*. (1993); Kakehi and Irikura (1996); Nakahara *et al.*. (1998)). In this paper, we discuss on the envelope inversion results of the 1993 Kushiro-oki earthquake (Mw = 7.6) and the 1995 Hyogo-ken Nanbu earthquake (Mw = 6.9),

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obtained using the method developed by Kakehi and Irikura (1996). Their method overcomes the problem of Green's functions mentioned above by using empirical Green's function approach. Detailed description of the method is done in the next section

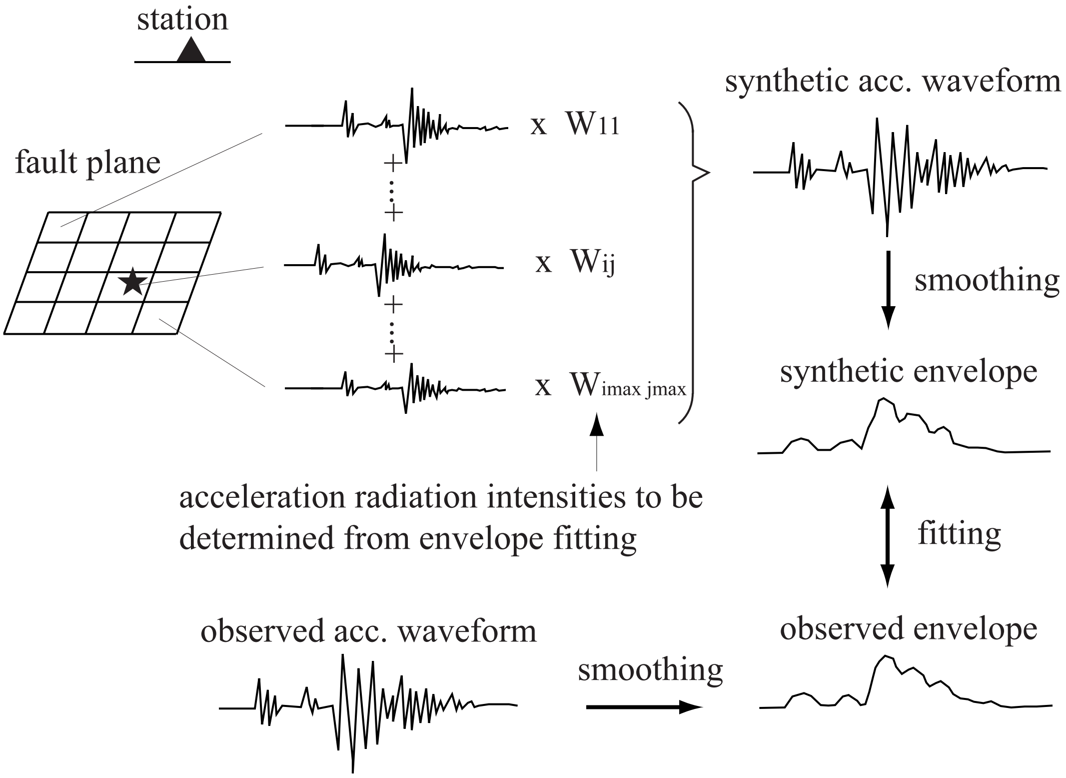

Figure 1: Schematic illustration of envelope inversion.

ENVELOPE INVERSION

It is impossible to perform a waveform inversion for waveforms with frequencies higher than 1 Hz. We do not have such fine temporal resolution as to fit the observed and synthetic high-frequency waveforms which are very oscillatory. By using envelopes instead of waveforms, however, we can apply inversion scheme to the analysis of high-frequency waves on the inversion scheme. We use the envelope inversion method developed by Kakehi and Irikura (1996). The concept of envelope inversion is shown in Fig. 1. The assumed fault plane is divided into meshes. The model parameters are the weights, which are called acceleration radiation intensities, and rupture times of the meshes (note that in Fig. 1 only weights are shown). The seismic waves from each meshes are calculated using Green's functions. The synthetic waveforms are obtained from superposition of the seismic waves from all the meshes on the fault plane. As mentioned above, we can not get waveform fitting between observation and synthesis in case of high-frequencies. Therefore, the observed and synthetic waveforms are smoothed into the observed and synthetic envelopes, respectively. Fitting is done between observed and synthetic envelopes. From the fitting of envelopes, best model parameters are estimated. Envelopes are calculated as running root mean square of acceleration seismograms with a certain time window width. Because the model parameters include rupture times and the calculation of envelopes is nonlinear, the inversion becomes nonlinear. Therefore, it is linearlized and solved iteratively.

To obtain accurate Green's functions is always an important problem to extract information of source from the observed seismograms. Actually, we hardly know a field whose underground structure is known with accuracy available for frequencies higher than 1 Hz. Therefore, Kakehi and Irikura (1996) adopted an empirical approach for the evaluation of Green's functions. They used Irikura (1986)'s method to synthesize a waveform of a large event from that of a small event. See Kakehi and Irikura (1996) for more detailed description of their envelope inversion method.

ANALYSIS OF THE 1993 KUSHIRO-OKI EARTHQUAKE

The 1993 Kushiro-oki earthquake, Japan (Mw = 7.6) was a very remarkable earthquake in two points. First, surprisingly large acceleration of 919 cm/s2 was observed at the Japan Meteorological Agency (called JMA hereafter) station Kushiro just above the hypocenter though its focal depth was very deep (107 km). Second, it occurred not on the interplate boundary in the subduction zone but inside the Pacific Plate subducting beneath the North American Plate. More strangely, its fault plane was determined to be horizontal from various mechanism analyses and aftershock distribution. This section briefly describes the analysis by Kakehi and Irikura (1996).

The data used for the inversion are the acceleration records observed at station AKS of Central Research Institute of Electric Power Industry and at stations URA and HAC of JMA. The M_{JMA} 4.9 aftershock (depth = 113 km) is used as the empirical Green's function event. The observed acceleration records of the mainshock and the aftershock are bandpass-filtered between 2 and 10 Hz. The fault plane is divided into 12 x 8 subfaults. Here, the size of the subfault corresponds to the source size of the EGF event. Each inversion mesh is composed of 2 x 2 subfaults in order to reduce the number of model parameters. This means the fault plane is divided into 6 x 4 inversion meshes. The RMS running window width for calculating envelopes is 5.0 s.

Fig. 2 shows the comparison of the observed and synthetic envelopes for the final solution. Fig. 3 shows the distribution of the acceleration radiation intensities determined from the envelope inversion. High-frequency waves between 2 and 10 Hz are little radiated around the rupture starting point indicated with a star but radiated mainly at the periphery of the fault plane. Takeo *et al.*. (1993) estimated the rupture process of this earthquake from the inversion of strong ground motion displacement waveforms. The slip distribution they obtained, which corresponds to the radiation of seismic waves whose period is around 10 s, shows the large slip is concentrated around the rupture starting point. The important result is that the distribution of radiation intensities on the fault plane differs depending on frequencies. The pattern of the large slip at the rupture starting point and the large radiation of high-frequency waves is explained with a simple crack model (Madariaga, 1976). This indicates that the 1993 Kushiro-oki earthquake had a rather simple rupture process. The large high-frequency radiation at the periphery of the fault plane is interpreted as the stopping phase.

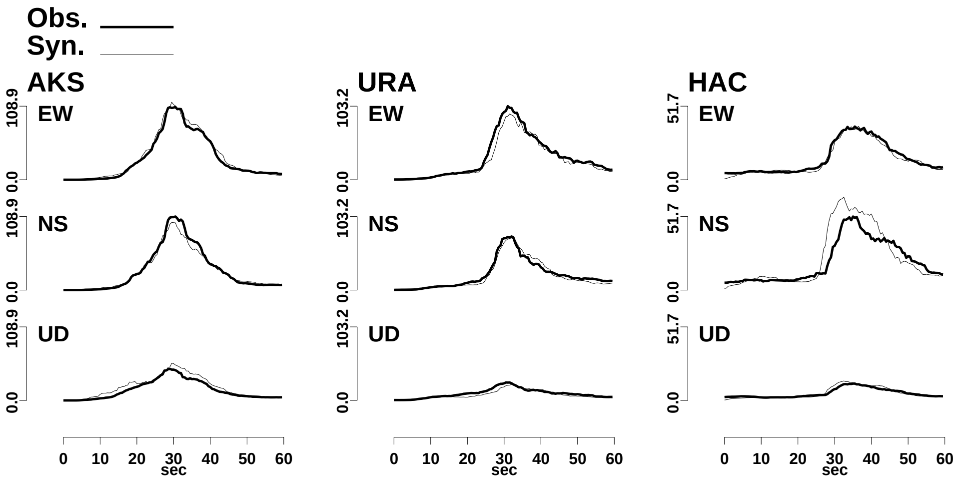

Figure 2: Comparsion of observed (solid line) and synthetic (thin line) envelopes for the final source model of the 1993 Kushiro-oki earthquake.

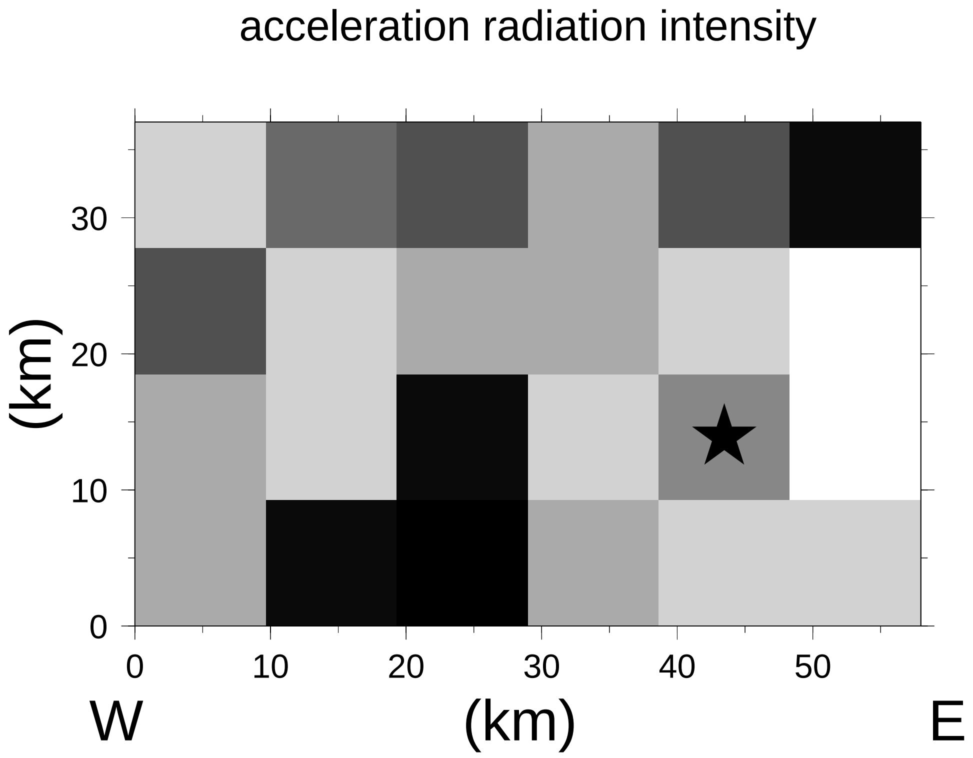

Figure 3: Acceleration radiation intensities on the fault plane of the 1993 Kushiro-oki earthquake estimated from the envelope inversion.

ANALYSIS OF THE 1995 HYOGO-KEN NANBU EARTHQUAKE

This section briefly describes the analysis by Kakehi *et al.*. (1996). The number of the stations used for the analysis is nine. Five stations (KOB, OSA, MRT, and MZH) belongs to JMA, and the four (MKT, ABE, SAK, and CHY) belongs to the Committee of Earthquake Observation and Research in the Kansai Area. As the records of the latter are velocities originally, they are numerically differentiated into accelerations. he synthetic waveforms at each station are calculated using the records of the three different aftershocks, each of which covers the northeastern area, central area, and southwestern area of the fault plane. The only exception is MRT, for which only one aftershock is available because of the large hypocentral distance. The observed acceleration records of the mainshock and the aftershock are bandpass-filtered between 2 and 10 Hz. The fault plane is divided into 33 x 12 subfaults (corresponding to the source size of the EGF event). Each inversion mesh is composed of 3 x 3 subfaults. Therefore, the fault plane is divided into 11 x 4 inversion meshes. The RMS running window width for calculating envelopes is 2.0 s.

Fig. 4 shows the comparison of the observed and synthetic envelopes for the final solution. Fig. 5 shows the distribution of the acceleration radiation intensities determined from the envelope inversion. The high-frequency waves are radiated at the area extending aslant from just below the Nojima Fault, where surface breaks appeared, to the bottom of the fault plane (A, B, and C in Fig. 5), just below Kobe City (D in the same figure), and the deepest part below Kobe City (E in the same figure). Sekiguchi *et al.*. (1996) obtained moment release distribution from the inversion of strong-motion displacement waveforms. They obtained large moment release at the Nojima Fault, which corresponds to the appearance of surface breaks there. Hanks (1974) reported that high-frequency waves are radiated when the rupture breaks the ground surface and named it breakout phase. Therefore, both of the large slip and the large radiation of high-frequency waves at the Nojima Fault can be explained by the appearance of surface breaks. The large high-frequency radiation denoted with B is located at the step-over of the fault planes just below the Akashi strait. This is explained by the interpretation that the discontinuity of the fault plane behaved as a geometrical barrier and generated high-frequency waves when ruptured. Kakehi and Irikura (1997) reported similar result. In their analysis of the 1993 Hokkaido Nansei-oki earthquake by envelope inversion, they found a large radiation of high-frequency waves just at the part where the aftershock distribution had a clear depth discontinuity. In contrast with the 1993 Kushiro-oki earthquake, which had a rather simple rupture process, the 1995 Hyogo-ken Nanbu earthquake had a very complicated rupture process.

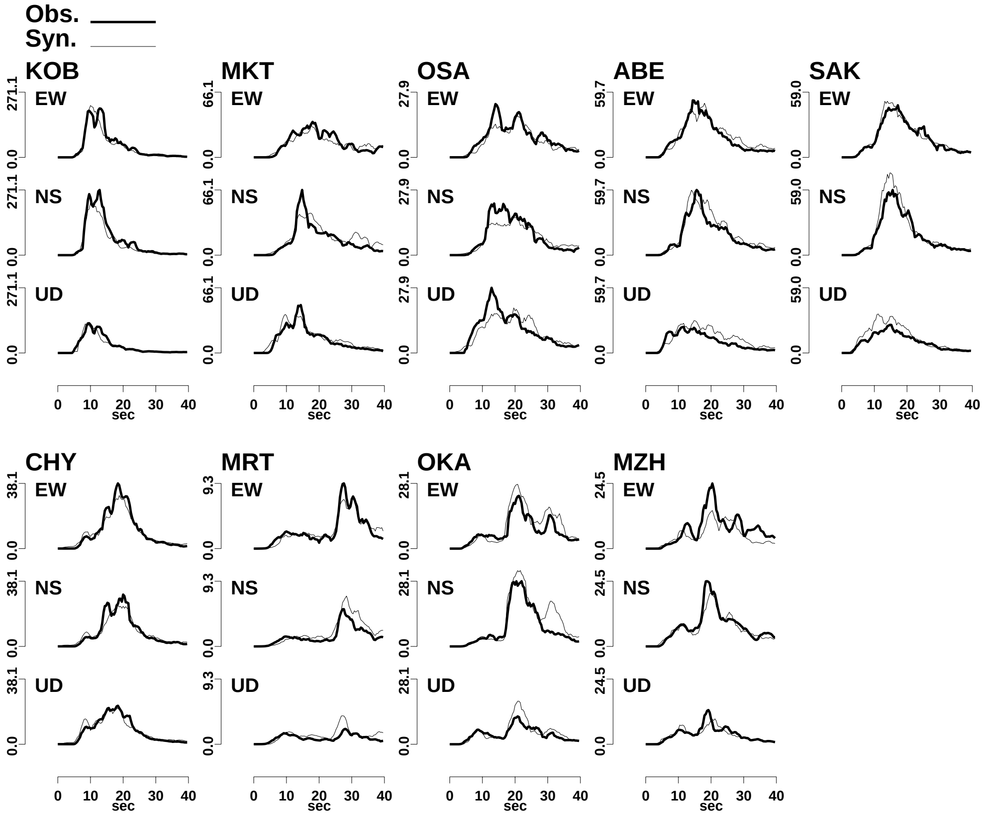

Figure 4: Comparsion of observed (solid line) and synthetic (thin line) envelopes for the final source model of the 1995 Hyogo-ken Nanbu earthquake.

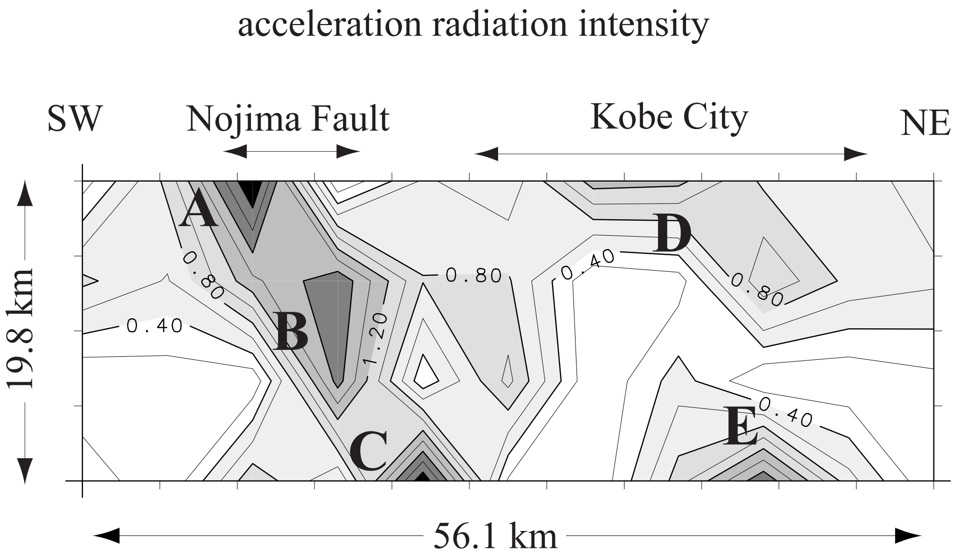

Figure 5: Acceleration radiation intensities on the fault plane of the 1995 Hyogo-ken Nanbu earthquake estimated from the envelope inversion.

DISCUSSIONS AND CONCLUSIONS

The most important finding brought by the analyses of high-frequency radiation process using envelope inversions is that the image of the source process basically differs between high- and low-frequencies. In case of simple source process, such as the 1993 Kushiro-oki earthquake, the distributions of radiation intensities of high- and low-frequencies are complementary to each other. This is expected from a simple crack model. In the meantime, if the rupture process is complicated, such as the case of the 1995 Hyogo-ken Nanbu earthquake, the relation between high- and low-frequency radiation is not so simple. Actually, in case of the 1995 Hyogo-ken Nanbu earthquake, both high- and low-frequency radiation are large at the Nojima Fault. Anyway, the number of this kind of analyses is too small at present to construct a general image of high-frequency source model. Now the availability of the envelope inversion method is confirmed, what is required next is to increase the number of the examples analyzed using it. Accumulation of the knowledge of the source process for wide frequencies will be a basic and valuable database for the source modeling for the quantitative strong ground motion prediction. At the same time, in order to give a theoretical backbone to the understanding of the high-frequency radiation process, an approach based on rupture dynamics to it is also required. In order to confirm the validity of the interpretation that the fault plane discontinuity can be a geometrical barrier, for example, such approach is indispensable.

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