ESTIMATION OF HIGH FREQUENCY ENERGY RADIATION (HFER) OF THE 2003 TOKACHI-OKI EARTHQUAKE USING EMPIRICAL GREEN'S FUNCTIONS

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ABSTRACT

We determined the centroids and stopping point of the high frequency energy radiation (HFER) of the 2003 Tokachi-Oki earthquake (Mw 8.1). We used tele-seismic data and basically followed the procedure of Gusev et al. (2007), who used the empirical Green's functions (EGFs) technique. We first chose several small events that occurred in the nearby region of the source. The waveform data were retrieved from the Data Management Center of the IRIS. We calculated correlation among their smoothed envelopes in the frequency bands, 0.4-1.2 Hz, 1.2-2.0 Hz, 2.0-3.0 Hz, and 3.0-4.0 Hz to obtain suitable EGFs. We calculated envelopes of the P-wave waveforms of the main shock and EGFs in the above four frequency bands, and smoothed them. Then, we performed deconvolution of the smoothed envelopes of the main shock using those of EGFs to obtain the HFER signals in each band for each station. A non negative constraint was applied to this calculation. Finally, we calculated the times and locations of the centroids and the stopping point of the HFER.

The obtained centroids of the HFER are consistent with those obtained by previous studies using different data sets and methods. The centroid times and source time are well constrained, while constraint for the centoid locations and stopping point are relatively weak.

Our results show that this method is applicable to determination of centroids of HFER of large earthquakes for which strong motion data is not available. One of the advantages of this method is that it is possible to obtain good azimuth coverage using tele-seismic waveform data.

Keywords: High frequency energy radiation, empirical Green's functions, Tokachi-Oki earthquake.

1. INTRODUCTION

China is one of the earthquake-prone countries, and has many damaging earthquakes in its history. One of the recent devastating earthquakes is the May 12, 2008 Wenchuan earthquake (Mw 8.1). Nearly 70,000 people have died, thousands are missing, and more than 1.5 million people lost their homes by this earthquake. Therefore, studies on earthquakes are very important in China.

Among seismological data analysis on earthquake sources, earthquake rupture studies can provide useful information to improve understanding of earthquake physics. Also, they provide useful information for strong ground motion simulation, which is effective for earthquake disaster mitigation. In the present study, in order to investigate the character of its high frequency energy radiation, we analyzed high frequency signals (0.4-4 Hz) of tele-seismic broadband seismograms of the September 25, 2003 Tokachi-Oki earthquake (Mw 8.1); we determined the centroids and stopping point of the high frequency energy radiation.

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2. DATA

We selected several events that occurred in the source area as candidates of EGFs in this study (Table 1). In this research, we need to choose EGFs with proper magnitude and good S/N ratio in order to obtain good accuracy in the following inversion. For this purpose, we checked the data quality visually and numerically after splitting them into the four bands and envelopes calculating.

Table 1 The candidate events for the EGFs of the 2003 Tokachi-Oki earthquake (after NEIC).

Time	Latitude	Longitude	Depth (km)	Mw
2003/10/09/06:53	41.56	143.87	31.0	5.6
2007/02/17/00:03	41.65	143.97	38.2	6.0
2009/06/05/03:30	41.82	143.45	29	6.4
2008/09/11/00:21	41.89	143.75	25.0	6.8

Broadband vertical velocity seismograms (P waves only) of our target earthquake (25 September, 2003, hypocenter=41.78 ° N, 143.86 ° E, depth=27km, and magnitude=8.1 after USGS) and the four earthquakes, are retrieved from the Data Management Center of the IRIS; their epicentral distances are constrained between 30° and 85° .

3. THEORY AND METHODOLOGY

3.1. Basic theory

The EGFs method is one of the most powerful methods for predicting strong ground motions of large earthquakes (e.g., Irikura, 1986). It is also applied to determining HFER of huge earthquakes (Gusev et al., 2007). It uses observed waveforms of small events as Green's functions to consider the effects of seismic wave propagation. Suitable events that can be EGFs of certain earthquake are not always available, which consequently put limitations on its application. In this study, there are some suitable aftershocks and small events that occurred close to the source region.

After records for each station for the main shock and the small event chosen as EGFs are smoothed properly, deconvolution is performed using the following convolution equation:

$$w_1(t) * w_a(t) = w_m(t) , \tag{1}$$

where $w_m(t)$ and $w_a(t)$ are squared envelopes of the main shock and the EGFs time series at each station, and $w_1(t)$ is the source signal of the main shock to be determined. By deconvolution for the equation (1), we can obtain $w_1(t)$. Since source radiations are always positive, we performed non negative inversion following Okamoto and Takenaka (2009).

We solved the damped least squares to avoid the numerical instabilities using

$$(G^T G + \alpha^2 I)\, m = G^T d , \tag{2}$$

where G is the kernel matrix consisting of the Green's functions, I is the identity matrix, α^2 is the damping factor, m is the model vector, and d is the data vector of the main shock (Hara and Yokoi, 2008).

Because of some noisy records, results obtained from deconvolution need to be checked carefully, and some of them should be discarded manually by visual check. Once we obtain the source radiations at each station, the following step is determining the centroid time and the signal duration. For the latter, we need to set a threshold for all the signal time series, and obtain the longest duration for all bands in each station. We set suitable threshold by trial and error.

3.2. Relative location method

Following Gusev et al. (2007), we use the relative location method to locate the centroids and the stopping point of the HFER. The following equations are used in this procedure:

$$M_t - (r_{1k}M_1 + r_{2k}M_2)/c = e_k \tag{3}$$
$$M_t^{fin} - (r_{1k}M_1^{fin} + r_{2k}M_2^{fin})/c = T_{fin}, \tag{4}$$

where M_t is the average retardation of radiation with respect to the origin time, and M_1 and M_2 donate relative location of centroid of HFER in the north south and eastwest directions, respectively. r_{ik} is the unit ray vector from the hypocenter to the k-th station. e_k and T_{fin} are the centrod time of HFER, and the signal duration used for determining stopping point, respectively. The terms marked by "fin" are corresponding to those for the stopping point. C is P wave's velocity here. As was mentioned by Gusev and Pavlov (1991), it is difficult to determine both Mt and the shift of the centroid in the vertical direction simultaneously, and the term corresponding to the latter is neglected in the above equations. In our analysis, we consider its effect to correct the observed centroid times by considering arrival time differences from the hypocenter to the centroid.

In coordinates {x, y, z} following N, E and Z directions, using formulas:

$$r_{1k}/c = dT/dx = \cos(Az)dT/d\Delta \tag{5}$$
$$r_{2k}/c = dT/dy = \sin(Az)dT/d\Delta, \tag{6}$$

we calculate the terms r_{ik}/c neglecting the geometrical non-linearity of the earth (see Figure 1). Here Δ and Az are station's epicentral distance and azimuth of the main shock, respectively.

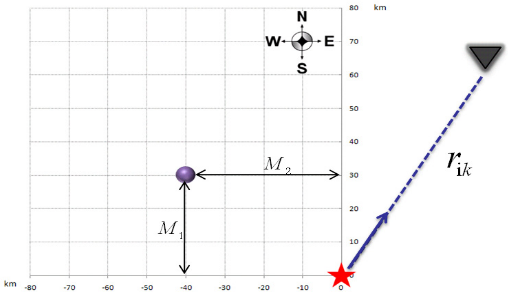

Figure 1. Map view of the relative location method. The red star denotes an epicenter and the purple circle represents a centroid of HFER or a stopping point. The blue arrow shows a unit vactor from epicenter to a station.

4. RESULTS AND DISCUSSION

4.1. Choosing EGFs

Choosing EGFs is a very important step in this study, and should be carried out carefully. In this section, we explain how we chose EGFs.

In order to select EGFs, first, we compared envelopes computed from seismograms observed at each station for some events that occurred in or near the source region.

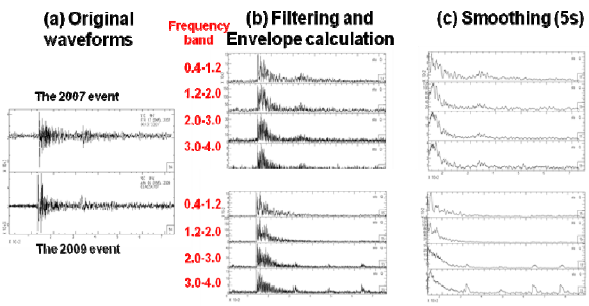

Figure 2. (a) The observed waveforms of the 2007 and the 2009 events recorded at station VLC, respectively. (b) Envelopes of the observed and filtered waveform. (c) Smoothed envelopes.

We applied band-pass filtering (the four frequency bands), then we calculated their P-wave envelopes, and smoothed them (using 5s' smoothing window). The procedure we conducted for the event pair between the 2007 and the 2009 earthquakes for station VLC is shown in Figure 2. We calculated all correlation coefficients among all event pairs in each frequency band for each station.

Figure 3 shows that the correlation coefficients between the smallest event and events with large magnitudes are smaller than those among other pairs. This suggests that the S/N ratio of the data from the smallest event is lower, and that the HFER signals from relatively larger events are consistent with each other.

The data from the smallest event do not have clear HF signals for some stations due to high noises, while large magnitudes imply that they have long source duration. Both of them cannot be good EGFs in this research. Therefore, we chose the 2009 earthquake as the EGFs in this study.

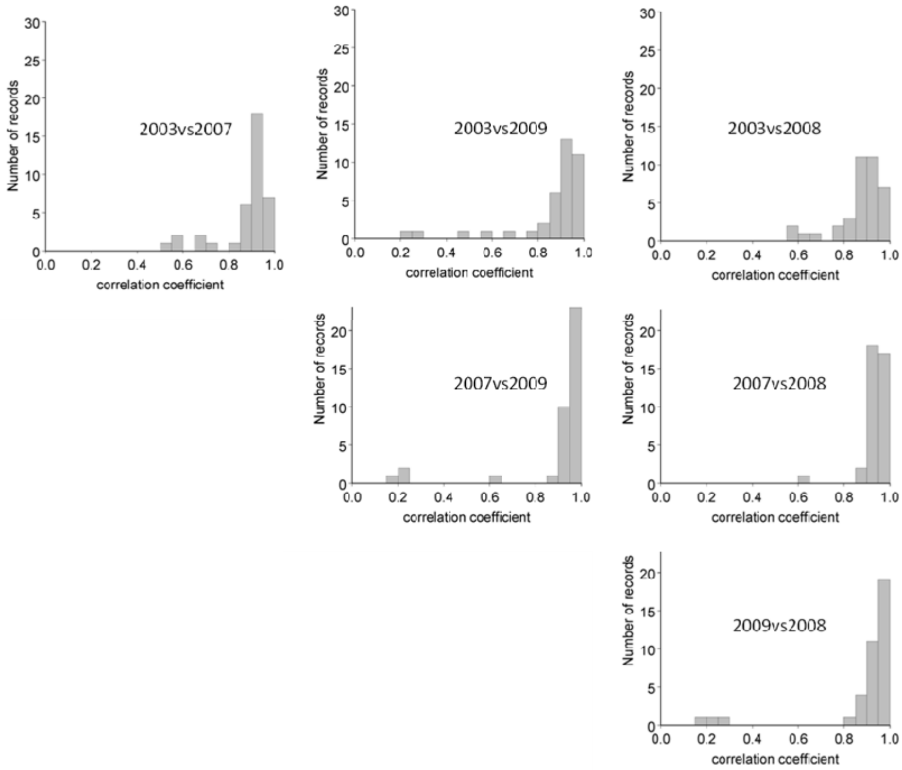

Figure 3. The correlation coefficients of all four bands of the events pairs among the four events

4.2. HFER signals determination

As we presented above, raw HFER signals are always distorted by wave scattering due to heterogeneities in the earth.

In order to obtain the HF signals of the main shock, we applied envelope inversion using EGFs chosen in the previous section, that is, the 2009 event.

We split the original waveform into four bands, which are 0.4-1.2, 1.2-2.0, 2.0-3.0, and 3.0-4.0 Hz. The procedure we conducted is as follows:

1. Retrieve data from IRIS DMC;
2. Filter them into the four bands using band pass filters;
3. Perform envelope calculation;
4. Smooth them using 5s' smoothing window;
5. Perform deconvolution using NNLS method;
6. Normalize the signals of the HFER.

First, we retrieved broadband vertical velocity data with epicentral distances between 30°and 85°from IRIS DMC. Then, the four bandpass filters were used to obtain the signals in each band. After that, envelope calculation and smoothing were done to the band pass seismograms. Figure 4 shows the centroid times and signal durations for four bands obtained for station VLC.

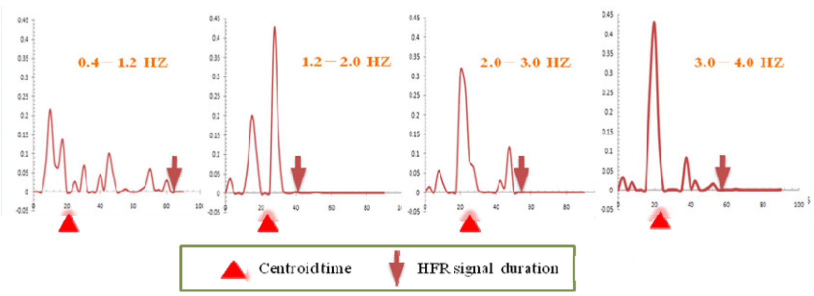

Figure 4. Schematic centroid times and signal durations for four bands in station VLC

Note that there are several apparent impulses in the obtained HF signals, which are likely to be strong energy radiation. This suggests that we may extract more information from these results, not only the centroids of the HFER, but also the locations of sub-radiators.

4.3. Times and locations of the centroids and the stopping point of the HFER

In the preliminary analysis in which the effect of the vertical centroid shift is not considered, the centroid location was determined near the northwestern edge of the rupture area suggested by previous studies. This indicates that the vertical centroid shift is about 30 km based on the assumed plate boundary in this region. Therefore, we corrected the observed centroid and stopping times considering the vertical centroid shift of 30 km. Figure 5 and Table 2 show the centroids of the HFER signals, and the stopping point of this event. It indicates that the centroid times of the HFER are about 30 s after the starting of the rupture, and the total HFER duration is about 60 s. The locations of the centoids of the HFER are all huddled in the northwest of the epicenter, and the stopping point is located in the even farther to the west. This indicates that the rupture propagated northwest, and stopped at the northwest side of the epicenter. Using the parameters we obtained from the inversion, we calculated the theoretical centroid times of the HFER for each frequency band in each station (Figure 6). We found overall agreement between the theoretically calculated and observed centroid times, although there are considerable scatteres between them.

Table 2. The times and locations of the centroids and the stopping point of the HFER. Mt, M1, M2 are the average retardation of radiation respect to the origin time, relative locations of centroids of HFER in the north south and eastwest directions, respectively. The errors are twice of their standard deviations.

Frequency band	**Mt**	**M1**	**M2**
0.4-1.2	32.89±0.40	82.92±8.68	-87.80±9.28
1.2-2.0	29.69±0.44	78.71±9.60	-48.89±9.90
2.0-3.0	30.00±0.50	83.44±9.60	-65.30±9.90
3.0-4.0	31.58±0.50	108.42±9.60	-87.32±9.90
Stopping point	59.67±0.42	75.35±8.98	-148.87±9.90

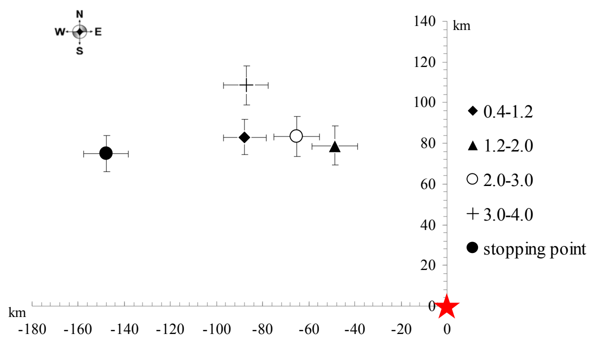

Figure 5. Spacial locations of the centroids the starting point of the HFER. The red star shows the starting point of the rupture, and the error bars show twice of the standard deviations.

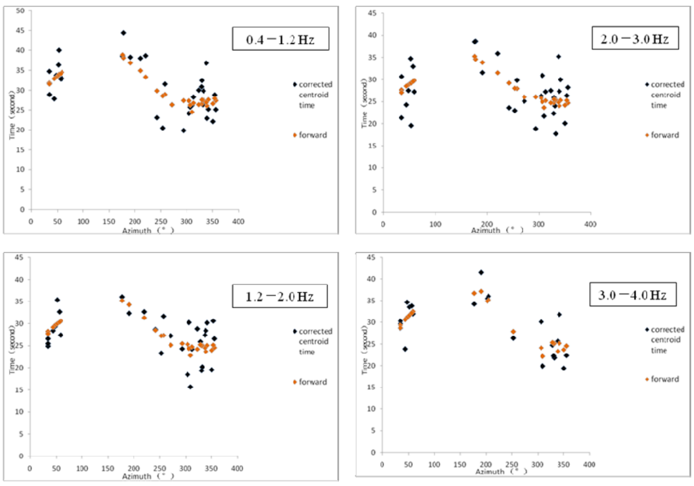

Figure 6. Comparison between the centroid times of the forward calculation using the parameters from the inversion and those of the observed ones in the four frequency bands.

Also, we found that the times, that is, Mts, are very robust and keep consistent even the damping factor and data checking were not carefully treated. On the contrary, locations of the centroids of the HFER and the stopping point are affected by data selecting and the threshold we chose for determining time duration.

Several studies have already been done on the source process of this earthquake using different methods and data sets. In terms of direction of the rupture propagation, centroid times and source duration, our results are consistent with them. As for centroid locations, our centroids are located near the northwestern edge of the rupture area, which seems different from other results, most of which suggests that the centroid of moment release is located around the center of the rupture area. This difference may indicate the difference between slip distribution, which is determined by other studies, and high frequency energy radiation distribution, which is obtained in this study. However, since, as was mentioned, the constraint for the centroid location is relatively weak, further analysis to improve its accuracy is required to discuss this difference.

5. CONCLUSIONS

We determined the centroids and stopping point of the HFER of the 2003 Tokachi-Oki earthquake. We used the empirical Green's functions (EGFs) technique following the procedure of Gusev et al. (2007). We found that the P-wave envelopes from small events in the nearby source region are similar to each other for most of the stations, which demonstrated the applicability of this approach. Also, we found that careful investigation and selection of EGFs are important for obtaining reliable results.

We performed deconvolution of the smoothed envelopes of the main shock using those of EGFs to obtain the HFER signals in each band for each station. A non negative constraint is applied to this calculation. Then, we calculated the times and locations of the centroids of the HFER and the stopping point. The centroid times and source duration are estimated to be about 30 and 60 s, respectively. The centroid locations suggest the northwestward propagation of the rupture. These results are consistent with other results obtained using lower frequency data. Our results show that it is possible to obtain the centroids of the HFER of large earthquakes using carefully chosen EGFs. The result shows that the centroid times can be determined reliably. The centroid locations are more difficult to be constrained as in the same accuracy as that for centroid time.

Compared to methods using strong motion records, the advantages of this method are as follows. First, due to the topographical features of some targets (such as that of in Tokachi-Oki), the strong motion records cannot surround the epicenter. This will affect results of inversions. In the method of the present study, we use tele-seismic waves, and the azimuth coverage of the data set is good. Systematic bias due to poor azimuth coverage of the data set is expected to be small. Also, it is easy to retrieve data and to implement the inversion. We plan to apply this method to a series of large earthquakes and discuss the characteristics of the HFER.

6. RECOMMENDATION

A set of large earthquakes should be analyzed if we are going to explore the physical meaning of HFERs. Furthermore, comparisons among earthquakes which are sorted by geodynamic environments are appreciated and will be one in the list of our future plan.

AKNOWLEDGEMENT

I would like to express my sincere gratitude to Dr. N. Hurukawa and Dr. B. Shibazaki for their useful comments in improving this study and manuscript.

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