13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 665

INVERSION OF SOURCE PROCESS IN CONSIDERATION OF FILTERED-ACCELERATION ENVELOPE

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SUMMARY

A new inversion technique using filtered acceleration envelope with emphasis on frequency-dependent properties of source process is presented. The technique uses strong motion prediction model EMPR (Earthquake Motion Prediction model on Rock surface) developed by Sugito et al. [1] which have been developed on the basis of the strong motion database. Filtered envelopes for the simulated motions are calculated for comparison with the observed motions. The least square method is then applied to solve the best pattern describing the relative distribution of seismic power from elemental sources on the fault plane. Numerical examples are shown for the inversion of source process of the 1999 Taiwan Chi-Chi earthquake. Frequency-dependent asperities are obtained for the low, mid, and high frequency ranges; the first one is consistent with far-field S wave inversion by Yagi et al. [2], the last one being with non-filtered acceleration envelope inversion. Successful results are also demonstrated in terms of reevaluation of time histories of non-stationary power spectra and spatial distribution of seismic intensity.

INTRODUCTION

The information on source process with sufficient accuracy is indispensable for the estimation of strong ground motion near the focal region. Hartzell and Heaton [3] proposed the waveform inversion method for the slip distribution using the long period wave such as the displacement wave and the Teleseismic Body-wave. Kakehi and Irikura [4] proposed the inversion method for the estimation of radiation pattern of the short period earthquake motion on the fault. They supposed that an acceleration wave with strong amplitude might not be appropriate for the analysis, consequently, the envelope of acceleration applied. This inversion method deals with the synthesized acceleration derived from the empirical Green's function technique [4]. For the applicaiton of the method, the foreshock or aftershock ground motion records from the relevant fault zone are indispensable, therefore, the applicability is limitted the in engineering point of view.

Nakahara et al. [5,6] developed the inversion technique for the radiation pattern of strong motion energy using the envelope of the band-pass filtered acceleration time history simulated for the given fault

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parameters. The method can identify the radiation pattern of strong motion energy for each defined frequency range. They demonstrated the different radiation patterns depending on the frequency ranges in case for the 1994 Sanriku Offshore Earthquake and the 1995 Hyogoken Nambu Earthquake.

Sugito et al. [1] have developed the strong motion predinction model, EMPR, dealing with the synthesis of the evolutionary spectra from individual successive small events of the main fault. In this paper the simulated ground motion by the EMPR is adopted as the Green's function for the inversion of the fault process. The envelope of acceleration as well as those for bandpass filtered acceleration obtained from the synthesis of the evolutionary spectra are dealt with.

In this analysis the radiation pattern of strong motion energy which is represented as the normalized coefficient for the superposition of evolutionary power spectra assigned for each sub-event. The proposed method is applied to the 1999 Taiwan Chi-Chi Earthquake.

OUTLINE OF SOURCE PROCESS INVERSION

Inversion procedure

Figure 1 shows the flow of the inversion method by Kuse et al [7]. As shown in Figure 1, the inversion method consists of two steps. In the analysis, the focus (latitude, longitude, depth) and the parameters regarding a fault plane (length, width, strike, dip angle) are dealt with as the given parameters.

In STEP 1, the seismic moment, M_0, and the propagation velocity of rupture, v_r, are identified. The details are presented by Kuse et al [8]. At this stage the asperity distribution is not considered for the fault plane. The two ground motion parameters are used for the inversion of M_0 and v_r; one is the acceleration total power, P_t, and the other, the strong motion duration, t_{90}. The definition of P_t and t_{90} are shown in Figure 2. The acceleration total power, P_t, defined by Equation (1) denotes square sum of the acceleration record.

$$P_t = \int_0^T \{x(t)\}^2 \, dt \tag{1}$$

where, P_t is the acceleration total power (cm^2/sec^3), $x(t)$ is the acceleration (cm/sec^2) at time t, T is the total time of recording (sec). The parameter, t_{90}, is defined as the duration from 5 to 95 % of the accumulation of acceleration power as shown in Figure 2.

This inversion procedure has been developed from the assumption following;

(1) The acceleration total power, P_t, is affected by the total energy release on the fault, and this energy release may be related to the seismic moment, M_0.

(2) The duration of strong motion depends strong on the size of fault and propagation velocity of fault rupture, v_r.

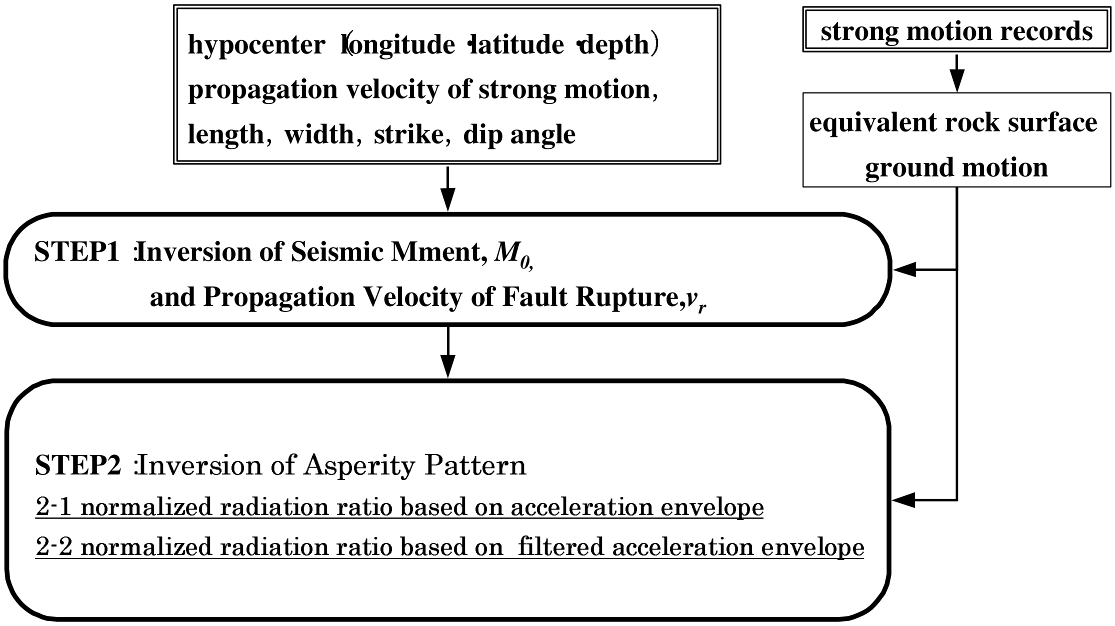


Figure.1 Outline for the Two Step-Inversion of Source Process

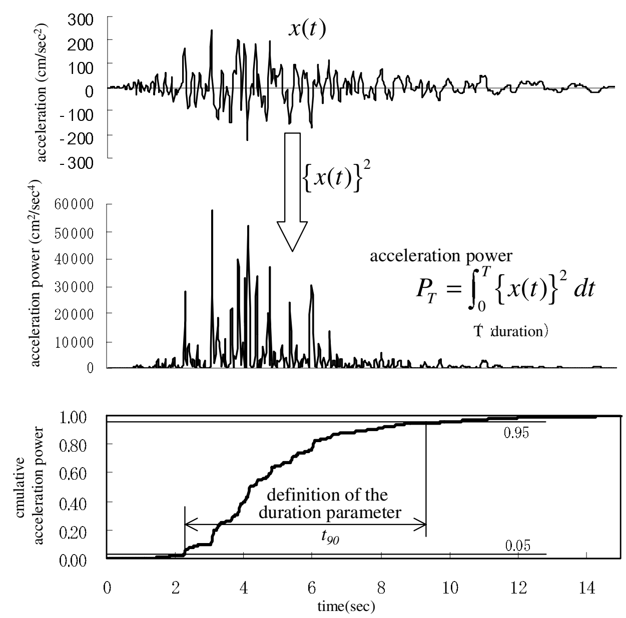


Figure.2 Definition of the Duration Parameter t_{90} with Acceleration Total Power P_t

In STEP 2, the inversion of normalized radiation ratio of acceleration power on the fault plane is performed for the given seismic moment, M_0, and propagation velocity, v_r, identified in STEP 1. The two types of inversion are examined; One deals with the envelope of acceleration time history (STEP 2-1), and the other deals with the envelope of bandpass-filtered acceleration time history for low, middle, and high frequency ranges (STEP 2-2). The detail of the STEP 2-2 procedure is presented in the following.

Estimation of radiation ratio of acceleration power based on the envelope of filtered acceleration

The inversion method deals with the envelope of bandpass-filtered acceleration time history as the Green's function. They are obtained from the synthesis of evolutionary power spectrum [9]. Figure 3 shows the flow chart of the inversion method. The procedure is in the following.

(1) The fault plane is divided equally into a set of subfaults, and the evolutionary power spectrum at the specific site from each subfaults, $G_{x,s}\left(t, 2\pi f\right)$, is determined by EMPR.

The total sum of these evolutionary power spectrum, $G_{x,syn}\left(t, 2\pi f\right)$, is obtained by the synthesis of $G_{x,s}\left(t, 2\pi f\right)$ on time axis.

(2) Then, the envelope of bandpass-filtered acceleration time history is calculated. The filtered acceleration power is determined in the following manner.
The envelope of bandpass-filtered acceleration can be represented by the synthesis of the evolutionary power spectra.

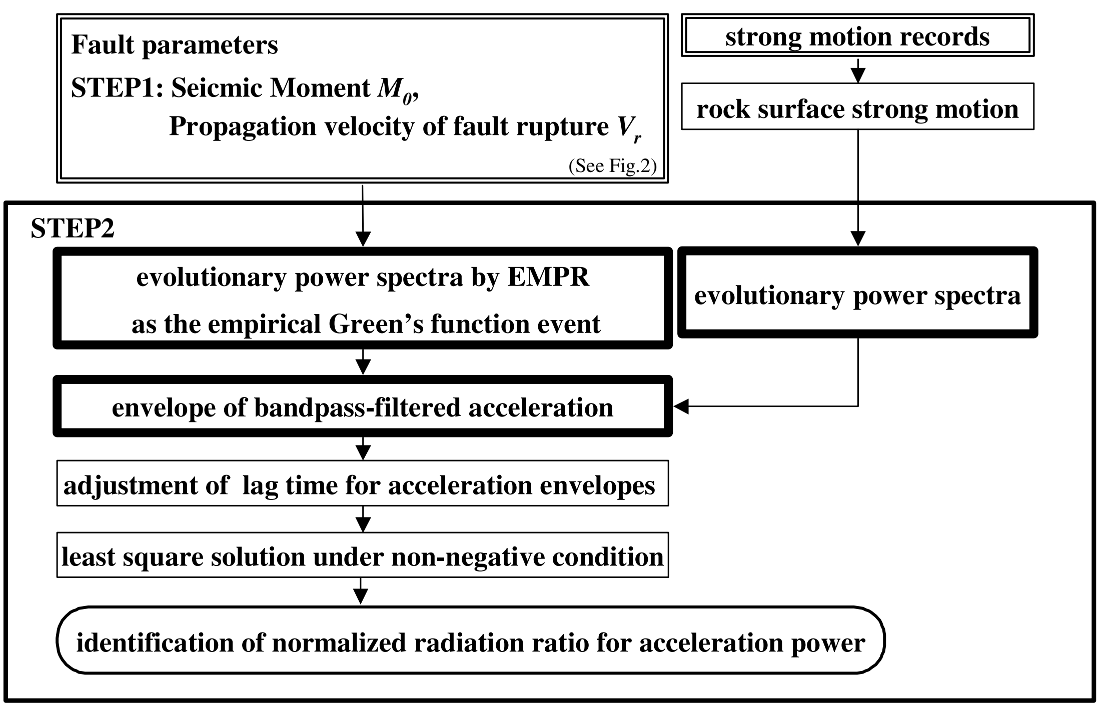


Figure.3 Outline for the Inversion of Normalized Radiation Ratio
Based on Filtered Acceleration Envelope

$$H_{syn}(t, f_l, f_u) = \int_{f_l}^{f_u} \sqrt{4\pi \cdot G_{x,syn}(t, 2\pi f)}\, df \tag{2}$$

Where, $H_{syn}(t, f_l, f_u)$ is the envelope of bandpass-filtered acceleration time history for the frequency range between f_l and f_u Hz.

(3) In the same way, the envelope of bandpass-filtered acceleration time history for the observation record, $H_o(t, f_l, f_u)$, is calculated for the frequency range between f_l and f_u Hz.

(4) Generally, there is a lag time on time axis between the centroid of the recorded and simulated acceleration envelope. It is indispensable manner to adjust the lag time for inversion analysis.

(5) With the use of $H_o(t, f_l, f_u)$ and $H_{syn}(t, f_l, f_u)$, the normalized radiation ratio based on filtered acceleration envelope can solve least square problem with non-negative constraints.

The least square problem is represented in the following Equation [10].

$$\begin{bmatrix} H_{s_{11}} & H_{s_{12}} & \cdots & H_{s_{1m}} \\ H_{s_{21}} & H_{s_{22}} & \cdots & H_{s_{2m}} \\ \vdots & \vdots & \ddots & \vdots \\ H_{s_{n1}} & H_{s_{n2}} & \cdots & H_{s_{nm}} \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_m \end{bmatrix} \cong \begin{bmatrix} H_{o_1} \\ H_{o_2} \\ \vdots \\ H_{o_n} \end{bmatrix} \tag{3}$$

The parameters in Equation (3) are in the following.

m : number of subfault

n : number of observation records

$H_{s_{ij}}$: evolutionary power spectrum

H_{o_i} : The evolutionary power spectrum of observation record

i : time step

j : subfault number

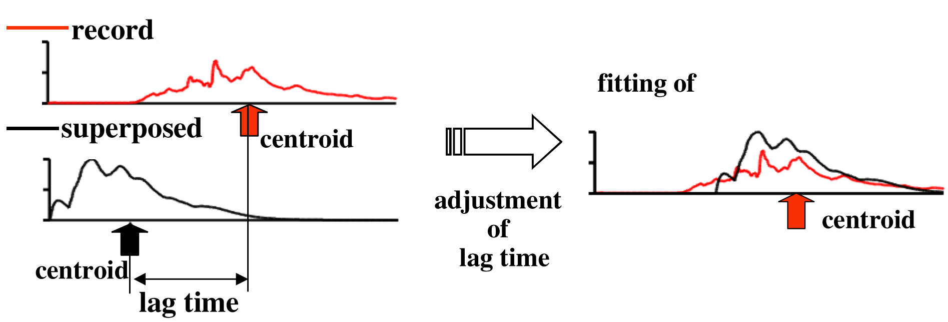


Figure.4 Adjustment of Lag Time for Accelerations Envelopes

APPLICATION TO THE 1999 TAIWAN CHI-CHI EARTHQUAKE

Normalized radiation intensity

The inversion method presented above is applied to the 1999 Taiwan Chi-Chi earthquake. Figure 5 shows locations of the strong motion stations, the stations applied for inversion analysis, the fault plane model, and the fault line appeared on the ground surface. The 42 horizontal component acceleration recorded at the 21 stations are used in the analysis.

Table 1 shows the given fault parameters and the estimated parameters (M_0, v_r) by SETP 1. The normalized radiation intensity is estimated using their parameters.

Table.1 Fault Parameters for the 1999 Taiwan Chi-Chi Earthquake

Fault Parameter		Value
Focus	Latitude (degree)	23.86
	Longitude (degree)	120.81
	Depth (km)	7.5
Fault plane (after Yagi and Kikuchi [2])	Length (km)	80.0
	Width (km)	40.0
	Strike (degree)	5
	Dip angle (degree)	30
Propagation velocity of strong motion (km/sec)		3.00
Propagation velocity of fault rupture v_r (km/sec) (Estimated by SETP1)		2.20
Seismic moment M_0 (N m) (Estimated by SETP1)		2.14×10^{20}

However, the EMPR that is used for the analysis is the strong motion prediction model on the rock surface. Therefore, the ground surface records should be converted to those on rock surface level, for the analysis. This analysis used the observation records on the ground surface, because there were no soil data nearby of the strong motion stations.

Figure 6 shows the normalized radiation coefficient of acceleration power for low, middle, and high frequency range, respectively. The envelope of band-pass filtered acceleration time history. The frequency range is fixed as 0.13~0.55Hz for low, 0.61~2.35Hz for middle, and 2.41~10.03Hz for high frequency range are used. It is observed that the radiation pattern strongly depends on the frequency range.

For the comparison, Figure 7 shows the normalized radiation ratio that have been obtained using the envelope of acceleration time history [7], and Figure 8 shows the distribution of coseismic slip estimated by Yagi et al [2].

It is observed that the distribution of coseismic slip by Yagi and Kikuchi [2] is compatible to the normalized radiation ratio for low frequency region, show in Figure 6(a), and that the normalized radiation ratio for high frequency region, show Figure 6(c), is similar to the result show in Figure 7.

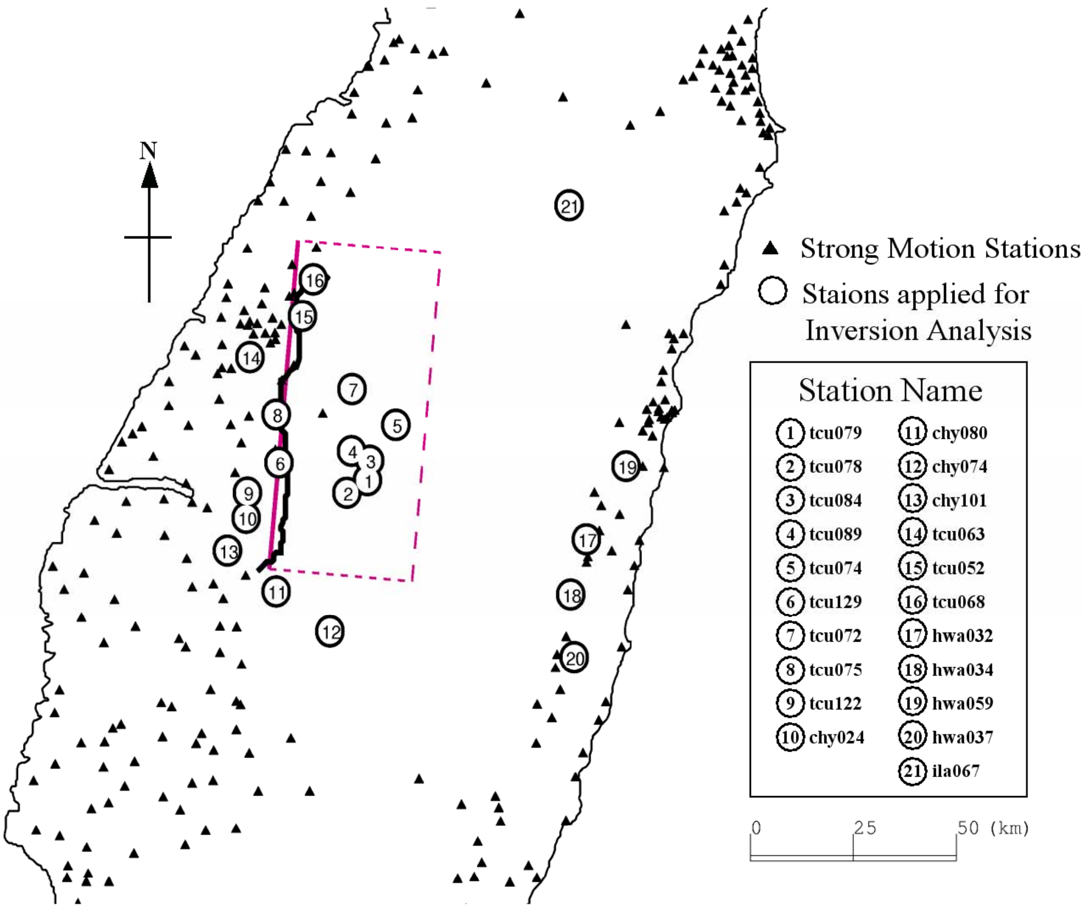


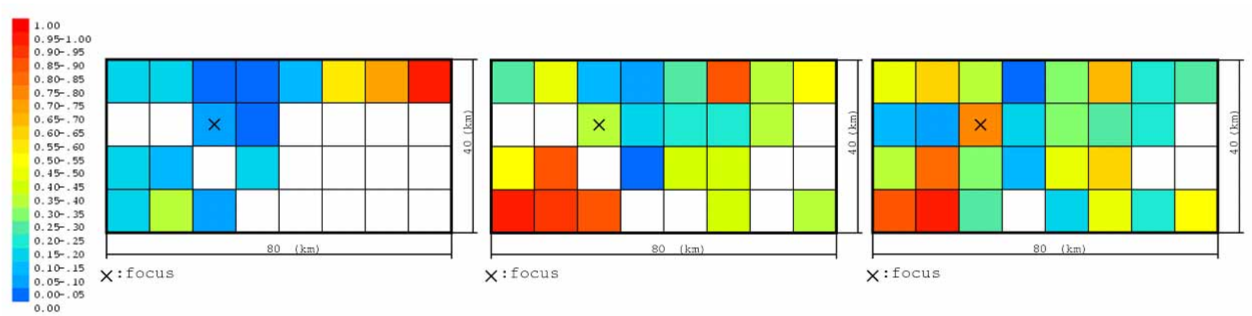
Figure.5 Location of Strong Motion Stations and Fault

Simulated acceleration time history based on the estimated radiation pattern on the fault

In this section, the validity of the inversion method is discussed regarding the similarity of the acceleration envelope, as well as the ground motion parameters. Figure 9 shows the envelopes both for recorded and simulated acceleration time history at the station 7(tcu072) show Figure 5. These envelope curves are smoothed by a 1.5 sec time window length.

Figure 10 shows the comparison of JMA seismic intensity scale at the observation sites. The JMA seismic intensity scale is determined from the acceleration time history modified by the filtering function. As shown in Figure 10. the JMA seismic intensity fluctuates by a large margin in case for records. One of the reason for this large fluctuation may be the effect of local soil condition. On the other hand, the JMA seismic intensity for simulated acceleration does not fluctuated very much.

However, they can estimate the broad pattern of those for recorded. It is also observed that the JMA seismic intensity obtained in case of the unique radiation pattern underestimate nearly for all the stations. The reason of this result is considered that, in case of the unique radiation pattern, the envelope of acceleration time history does not have a peculiar peak.



(a) 0.13~0.55Hz (b) 0.61~2.35Hz (c) 2.41~10.03Hz

Figure.6 Relative Ratio of Bandpass-filtered Acceleration Envelope

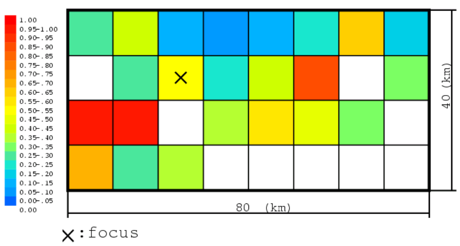


Figure.7 Relative Ratio of Acceleration Envelope [8]

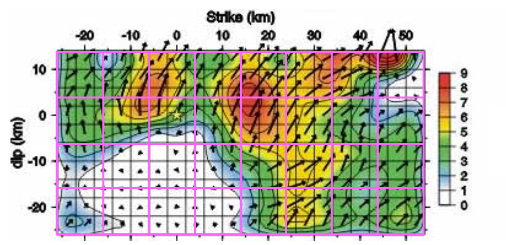


Figure.8 Distribution of Fault Slip (Yagi and Kikuchi [2])

CONCLUSIONS

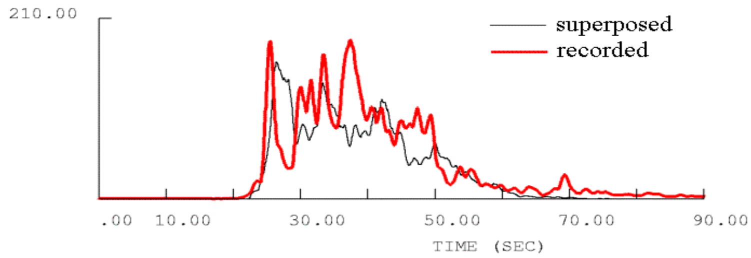
An inversion technique of source process was discussed, specially focusing on the radiation pattern of strong motion energy on the fault plane. The major results derived here may be summarized as follows.

1.A new inversion technique using filtered acceleration envelope was presented. The radiation pattern of strong motion energy on the fault plane was obtained individually for low, middle, and high frequency regions. In this technique the synthesized evolutionary power spectra given by the strong motion prediction model, EMPR, were incorporated as the Green's function.

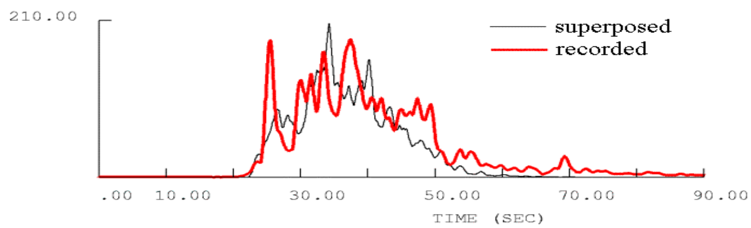
2.Numerical examples were shown for the inversion of source process of the 1999 Taiwan Chi-Chi Earthquake. The frequency dependent asperities, in another word, radiation pattern of strong motion energy, were demonstrated for the low, middle, and high frequency ranges. It was shown that the asperity for low frequency range was consistent with far-field S-wave inversion by Yagi and Kikuchi [2]. It was also recognized that the asperity for high frequency range was rather consistent with those obtained from the inversion using the non-filtered acceleration envelope.

3.The validity of the technique was examined in terms of the similarity of the acceleration envelope between simulated and observed strong motion time histories. The JMA seismic intensity scale was also compared at the strong motion stations.

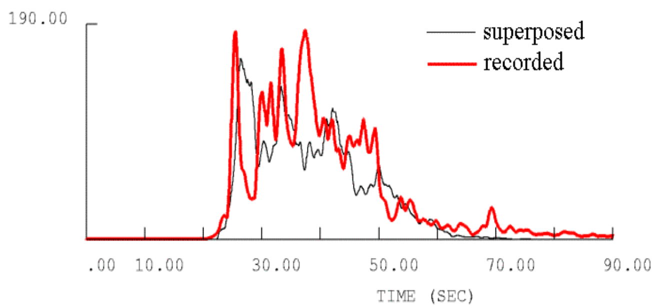
The strong motion records from the 1999 Chi-Chi Earthquake, which were used in this study, have been obtained on sedimentary sites. The effect of local soil conditions could be included in these records, and this may be one of the factor for estimation error. Further study is required in this point.



(a) Uniform Radiation Ratio



(b) Radiation Ratio Based on Acceleration Envelope



(c) Radiation Ratio Based on Bandpass-filtered Acceleration Envelope

Figure.9 Comparison of Envelope of Recorded and Simulated Acceleration Time Histories.

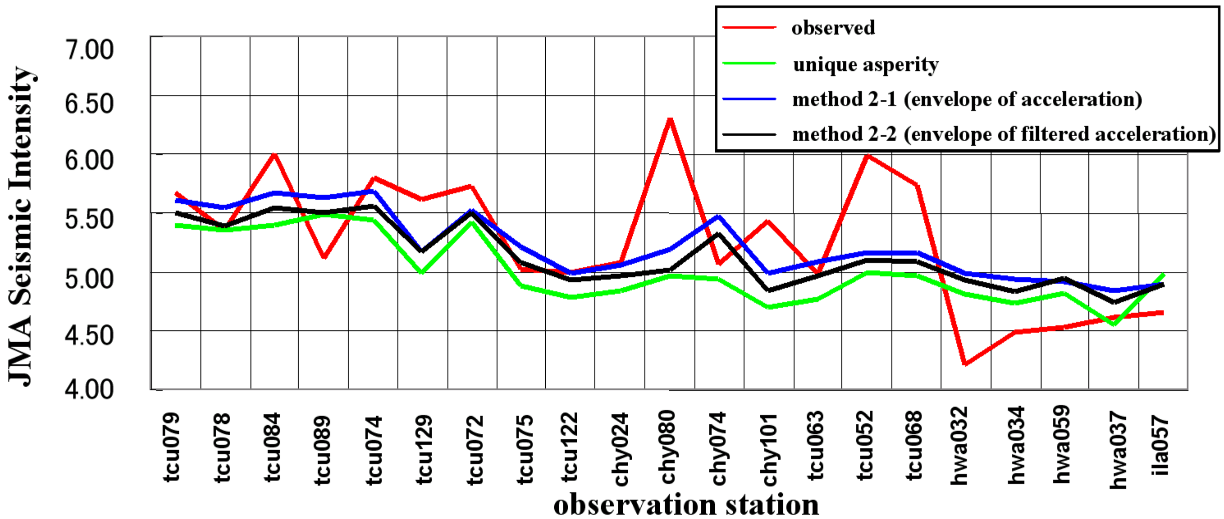


Figure.10 Comparison of JMA Seismic Intensity

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