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Estimation of strong motion generation area based on acceleration records during the 2011 off the Pacific coast of Tohoku Earthquake.

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Abstract

Detailed parameters of source process are indispensable for precise evaluation of ground motion characteristics in near-source region. Many studies have been devoted to development of inversion techniques based on observed waveforms such as far-field body waves, displacement motions, and acceleration envelopes. In those studies, however, less attention has been paid to short period contents of strong motions that have great influence on structures.

The prompt estimation of the seismic intensity distribution based on the information on fault process is specially required for the initial and effective restoration program. For prompt estimation, the simulation of strong motion that used the source process is need. This study deals with the inversion technique of source process based on the acceleration envelope. In this study, the strong motion generation area is represented by the normalized coefficient for the superposition of the evolutionary power spectra for each sub-event in the EMPR(Earthquake Motion Prediction model on Rock surface). The validity of the technique is examined in the case of the 2011 off the Pacific coast of Tohoku Earthquake.

During the 2011 off the Pacific coast of Tohoku Earthquake, strong motion records at many observation stations were obtained by KiK-net which is the observation network of National Research Institute for Earth Science and Disaster Prevention. In this study, the dataset of strong motion records that were observed by KiK-net stations, were used. Generally two seismometer both on ground surface and underground base rock level are set in the KiK-net system. Therefore, the records are converted to those for rock surface ground motion on the basis of the response analysis code, FDEL(Frequency Dependent Equi-Linearized technique). The inversion technique by use of the acceleration envelope is applied to this earthquake. The distribution of strong motion generation area on the fault plane, which represents the relative contribution ratio of acceleration power release, is obtained.

The result was compared with those by other studies, and they were comparatively agreed with. The results demonstrate the validity of the estimated distribution using the inversion technique of the 2011 off the Pacific coast of Tohoku Earthquake.

Keywords: waveform inversion, strong motion generation area, the 2011 off the Pacific coast of Tohoku Earthquake

1. Introduction

The 2011 Tohoku Earthquake that occurred in March 11, 2011, was a devastating earthquake. According to the Fire and Disaster Management Agency [1], human damage was 19,418 fatalities, 2,592 missing, and 6,220 injured. The damage of the dwelling houses was 121,809 collapses, 278,496 half-collapses, 744,190 partially-collapses, 3,352 inundation above floor level.

In this earthquake, many strong motion records were obtained by K-NET and KiK-net [2], which are the observation network operated by National Research Institute for Earth Science and Disaster Prevention. Those records provided useful information for estimation of source process. This study deals with the inversion of the SMGA (Strong Motion Generation Area) of the 2011 Tohoku earthquake, estimated using the inversion technique developed by Kuse et al. [3]. In this study, SMGA is represented by the normalized coefficient for the superposition of the evolutionary power spectra assigned for each sub-event in the EMPR (Earthquake Motion Prediction model on Rock surface) [4]. Data used for inversion are acceleration envelopes calculated using acceleration records from KiK-net database. In the following part of this paper, we outline the inversion technique used for this study and its application to estimation of the source process in the 2011 Tohoku earthquake.

2. Outline of source process inversion

2.1 Outline of source process inversion

Fig. 1 shows the flow of the inversion method by Kuse et al. [3]. In the analysis, the location of hypocenter (latitude, longitude, depth) and the fault parameters (length, width, strike, dip angle) are dealt with as the given parameters. The inversion method consists of two steps: STEP 1 for estimation of the seismic moment and the propagation velocity of fault rupture and STEP 2 for inversion of SMGA.

In STEP 1, the seismic moment, M_0, and the propagation velocity of rupture, v_r, are identified. The details are described in Kuse et al. [5]. At this stage the SMGA on the fault plane is not considered. 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 Pt and t90 are shown in Figure 2. The acceleration total power, P_t, defined by Eq. (1) represents the square sum of acceleration time history over the total record length T:

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

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 record length of the accelerogram (sec). The parameter, t_{90}, represents the duration defined as the time length between 5% and 95 % in terms of the accumulation of acceleration power as shown in Fig. 2.

Next, in the STEP 2, the inversion of normalized ratio of released acceleration power on the fault plane is performed using the seismic moment, M_0, and the propagation velocity of rupture, v_r, obtained in STEP1. Kuse et al. [3] proposed two alternative ways of processing acceleration time histories; one deals with the envelope of acceleration time history, and the other deals with the envelope of bandpass-filtered acceleration time history for low, middle, and high frequency ranges. In this paper, the envelope of acceleration time history for the estimation of SMGA was employed.

The outline of STEP2 procedue is presented in the following.

(1) The fault plane is divided into a set of equal subfaults, and the acceleration time history at the specific site from each subfaults is determined by EMPR.

(2) The acceleration time history from the subfault is calculated based on EMPR using the following equation:

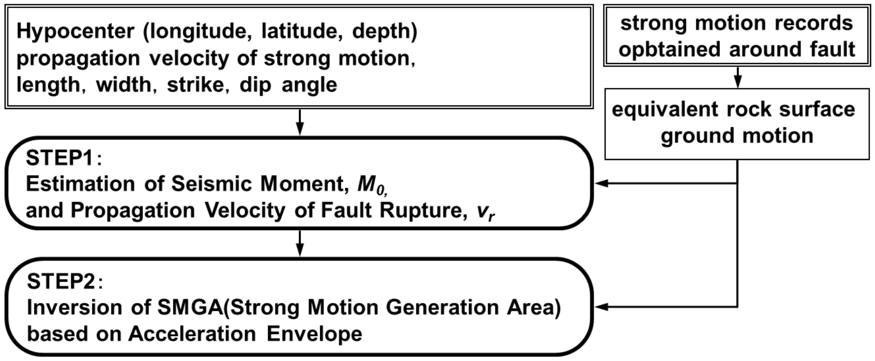

Fig. 1 – Outline for inversion of source process

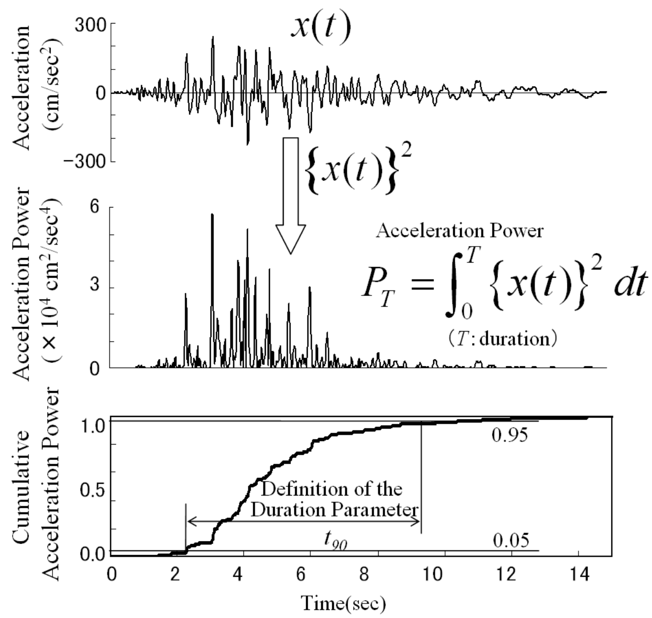

Fig. 2 – Definition of duration parameter t_{90} with acceleration total power P_T

$$x_{s_{ij}}(t) = \frac{N_G(M_0)}{N_x \cdot N_y} \sum_{k=1}^{m} \left\{ \beta\left(f_k, M_0\right) \sqrt{4\pi \cdot G_{ij}\left(t, 2\pi f_k\right) \Delta f} \cos\left(2\pi f_k t + \phi_k\right) \right\} \tag{2}$$

where, $x_{s_{ij}}(t)$ is the acceleration time history from the subfault $i\,j$, i is the element number along the fault length, and j is that along the fault width, m is the division number of frequency, $N_G(M_0)$ is the non-integral number of superposition that is equal to M=6 in EMPR, N_x and N_y are division numbers along fault length and width, $\beta\left(f_k, M_0\right)$ is the variation of correction factor for the frequency, $G_{ij}\left(t, 2\pi f_k\right)$ is evolutionary power spectrum of time t and frequency f_k, Δf is the step size of the frequency, φ_k is independent random phase angles distributed over 0-2π.

(3) By synthesizing the subfault-generating acceleration time histories obtained using Eq.(2), acceleration time history, $x_{syn}(t)$, is simulated. On this basis, an envelope acceleration time history, $y_{syn}(t)$, is calculated. Here, the envelope acceleration time history is defined as the square root of smoothed time history of square of

the acceleration time history. In the same way, the envelope acceleration time history, $y_0(t)$, is calculated using the observed time history, $x_0(t)$, and the envelope acceleration time history from the subfault, $y_{s_{ij}}(t)$, is calculated using the $x_{s_{ij}}(t)$.

(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 $y_0(t)$ and $y_{s_{ij}}(t)$, the asperity pattern can be obtained by solving least square problem with non-negative constraints from the following equation:

$$\mathbf{y_s} \cdot \mathbf{r} \cong \mathbf{y_o} \tag{3}$$

where, $\mathbf{y_s}$ is the data matrix of the acceleration envelope from subfault, $\mathbf{y_o}$ is the data vector of the observed acceleration envelope, $\mathbf{r}$ is the solution vector of the SMGA.

2.2 Conversion of the Strong Motion Records on the Rock Surface

In this study, the dataset of strong motion records that were observed by KiK-net [1] stations, were used. Generally two seismometer both on ground surface and underground base rock level are set in the KiK-net system. The inversion method used here is based on the strong motion prediction model, EMPR (Earthquake Motion Prediction model on Rock surface) [4]. The EMPR that was used for the analysis is the strong motion prediction model on the rock surface that was defined as the shear wave velocity of 400-600m/sec. Therefore, as shown Figure 1, these records were converted to those on the rock surface level with the shear wave velocity of approximately 400-600m/sec.

Fig. 3 shows the outline of conversion for the strong motion records. First, the record on rock surface level (over 500m/sec) was converted based on the soil profile models for these observation stations. The response analysis of layered ground, using the program code FDEL (Frequency Dependent Equi-Linearized technique) [6], has been applied. In this analysis, the lower limits of damping h_{min} for the rock and harder layer (over 500m/sec) was fixed as h_{min}=2.5% based on Enomoto et al. [7]. In case of other soils (clay, silt, sand, gravel), the lower limit was fixed as h_{min}= 5%.

Next, the free-rock surface ground motions were converted to those for the shear wave velocity of 500m/sec based on Midorikawa [8]. The amplification of earthquake motion from the seismic bedrock (Vs=3,000m/sec) to the surface is represented in the following equation.

$$\begin{aligned} A_v &= 170\, V_s'^{\,-0.6} & \left(V_s' < 1{,}100 \ \ \mathrm{m/sec} \right) \\ &= 2.5 & \left(V_s' \geq 1{,}100 \ \ \mathrm{m/sec} \right) \end{aligned} \tag{4}$$

where, A_v is the amplitude ratio of maximum velocity from the seismic bedrock to the surface, V'_s is the average of shear wave velocity at 30m below the surface of ground (m/sec).

The correction factor, A, of acceleration time history from rock surface level of V_s=V_{sx} to V_s m/sec is given in the following.

$$A = \frac{A_v(500)}{A_v(V_{sx})} \tag{5}$$

where, A is the correction factor of the earthquake motion, $A_v(500)$, $A_v(V_{sx})$ are the amplitude given Eq.(5) , V_{sx} is the shear wave velocity on the rock surface at each individual KiK-net site (See Fig.3).

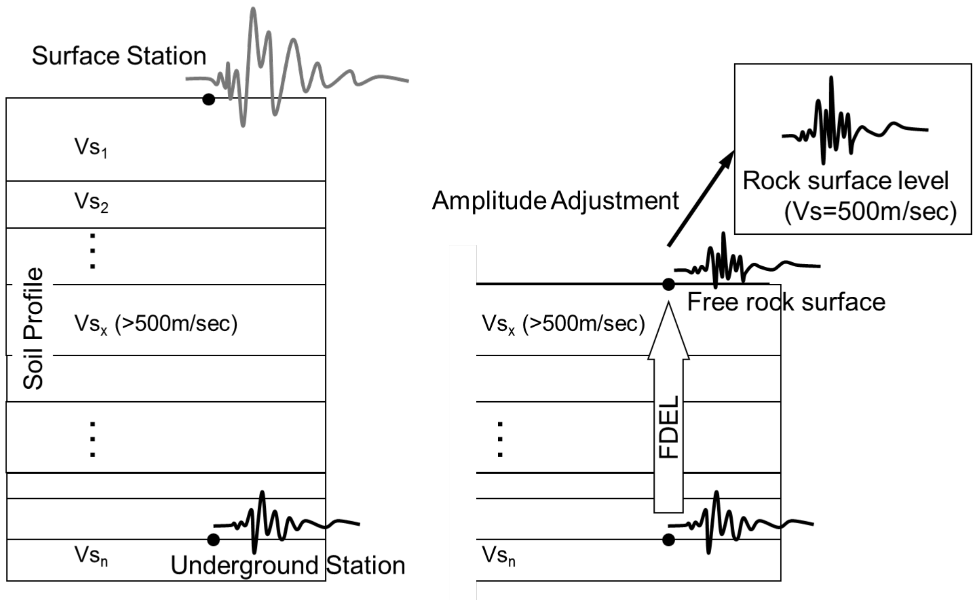

Fig. 3 – Schematic diagram for calculation of rock surface ground motion with shear wave velocity of 500m/sec

3. Application to the 2011 off the pacific coast of Tohoku Earthquake

The inversion method presented above was applied to the 2011 off the Pacific coast of Tohoku Earthquake. The dataset of strong motion records obtained during this earthquake was used. Fig. 4 shows location of the fault plane and the strong motion records obtained of KiK-net [2] around focal region. These records used in the analysis were obtained at the stations represented by circled numbers in Fig. 4. As previously mentioned, these records were converted to those on rock surface level with the shear wave velocity of 500m/sec.

The fault parameters were as below. The seismic moment M_0 was 6.72×10^{22} Nm, and, the propagation velocity of fault rupture V_r was 2.55 km/sec. As shown in Fig. 1, these parameters were estimated through STEP1. The fault plane used parameters that were estimated by Japan Meteorological Agency [9]. The Fault length was 400 km, width was 150km, strike was 201 degrees, dip angle was 9 degrees. The distribution in Fig. 4 shows the SMGA that was estimated by using the inversion technique developed by Kuse et al. [3]

The validity of the estimated SMGA is discussed regarding the similarity of the acceleration envelopes. Fig. 5 shows the envelopes both for recorded and simulated acceleration envelopes. The records are converted to rock surface level with the shear wave velocity of 500m/sec. These acceleration envelopes are smoothed by the rectangular window of 1.5 sec widths. As shown Fig. 5, there are differences of the simulated envelopes at few stations, but most simulated acceleration envelopes can confirm with reproducibility of recorded acceleration envelope.

Fig. 6 shows the comparison of JMA seismic intensity scale at the observation stations. The JMA seismic intensity scale is determined by use of three components of acceleration time histories processed with a specific band-pass filter prescribed by JMA. In this Figure, the JMA seismic intensity is calculated of horizontal components of acceleration time histories that was shown in Table 1. As shown in Fig. 6, the JMA seismic intensity simulated by using the estimated SMGA were lower than the recorded. These strong motion were seen the shape peak at the Fig. 5 and there were the points that the error was seen in the recorded acceleration envelope and the simulated acceleration envelope.

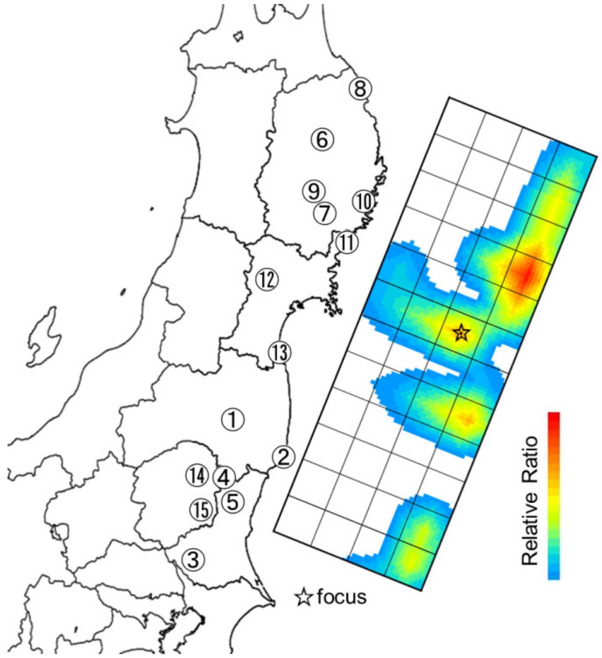

Fig. 4 – Location of strong motion stations and fault plane (distribution on fault plane is estimated SMGA. The circled number represents location of observation stations.)

Table 1 – List of strong motion records

No.	Station Code	Maximum Acceleration on Soil Surface (cm/sec^2)		Maximum Acceleration on Rock Surface (Vs=500m/sec) (cm/sec^2)	
		EW	NS	EW	NS
①	FKSH09	411.15	−421.56	509.23	371.03
②	FKSH14	−386.28	349.45	−709.31	485.78
③	IBRH10	295.77	272.35	281.81	−286.99
④	IBRH12	−524.85	−593.21	−365.27	−393.47
⑤	IBRH16	−589.86	−530.76	−387.39	−415.29
⑥	IWTH02	−501.76	−518.92	−238.30	−210.31
⑦	IWTH04	377.95	−310.53	418.21	−490.13
⑧	IWTH08	113.06	−116.08	62.02	−91.90
⑨	IWTH22	−302.01	−265.97	306.28	−250.88
⑩	IWTH23	−511.79	367.21	−378.26	354.05
⑪	MYGH03	−306.33	290.22	481.38	−576.30
⑫	MYGH05	−410.65	−505.67	−379.48	−323.30
⑬	MYGH10	−830.85	−889.53	−387.23	381.82
⑭	TCGH10	−585.37	−592.91	−511.55	372.26
⑮	TCGH16	1133.23	−802.40	−593.31	574.13

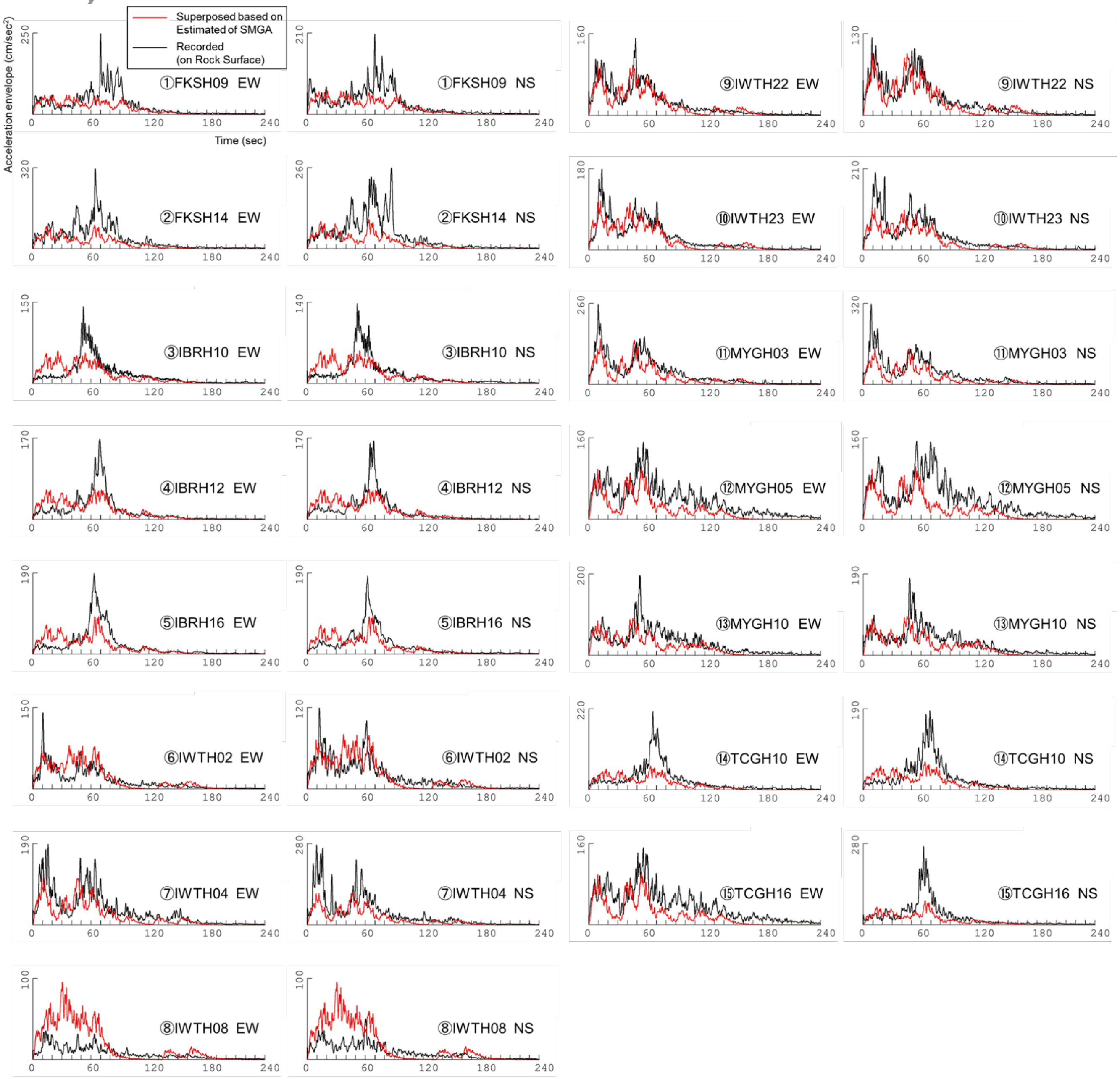

Fig.5 – Comparison of Acceleration envelopes of recorded and simulated acceleration time histories

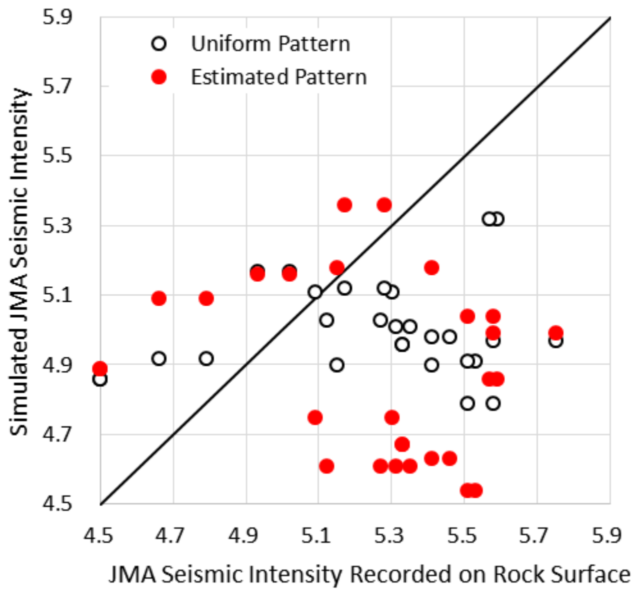

Fig.6 – Comparison of JMA seismic intensity (on the rock surface)

4. Conclusions

In this study, the distribution of SMGA for the 2011 off the Pacific coast of Tohoku Earthquake, was estimated by using the inversion technique developed by the authors. The major results derived here may be summarized as follows.

(1) The dataset of strong motion records on rock surface for the 2011 off the Pacific coast of Tohoku Earthquake have been obtained. The original acceleration records were obtained at underground bed rock level in KiK-net observation systems.

(2) The SMGA was estimated by an inversion technique developed by the authors. In the analysis, the acceleration envelope for the unit sub-event motion given by the strong motion prediction model, EMPR, was applied. The SMGA obtained in this study represents the relative ratio of release of acceleration power over the fault.

(3) The rock surface motions were simulated for the observation points on the basis of the estimated SMGA by using the simulation technique, EMPR. The simulated rock surface motions were compared with observed motions in terms of the acceleration envelope. The result demonstrated the validity of the inversion carried out in this study.

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