Strong motion generation area modelling of the 2008 Iwate earthquake, Japan using modified semi-empirical technique

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The Iwate–Miyagi earthquake (M_w 6.9) of 14 June 2008 is one of the largest intraplate earthquakes that struck north-east Japan. This earthquake has produced the largest peak ground acceleration (PGA) ever recorded. The acceleration values 4022 and 1036 gal were observed at the surface and borehole accelerometers of IWTH25. To understand the cause of this extremely large acceleration, it is highly essential to obtain the detailed rupture process of Iwate–Miyagi earthquake. The present paper estimates the rupture model for this earthquake using the modified semi-empirical technique (MSET). The detailed analysis proposes one strong motion generation area (SMGA) in the rupture plane and nucleation point in the extreme western corner of the SMGA. Using this estimated source model, a satisfactory match is observed between the simulated and actual records. The quantitative analysis of these waveforms provides an almost 1:1 match for PGA values. Furthermore, the variation of these PGA values with epicentral distance shows similar attenuation rate. These results confirm the reliability of MSET and the estimated source model of this earthquake. To the best of our knowledge, this study is the first to model SMGAs in the rupture model using MSET and provides sufficiently reliable information which will be useful for seismic hazard prevention management.

Keywords. 2008 Iwate–Miyagi earthquake; semi-empirical; SMGA; high-frequency records.

1. Introduction

The 2008 Iwate–Miyagi earthquake (M_w 6.9) was a reverse-fault-type crustal earthquake that occurred in the central portion of north-east (NE) Japan on 14 June 2008. Table 1 illustrated the earthquake parameters. This earthquake caused 23 casualties, 450 injuries and damaged about 2000 houses. This earthquake produced the largest peak ground acceleration (PGA) at IWTH25

station located just above the hypocentre. To clarify the cause of this extremely large acceleration, it is vitally important to obtain the detailed rupture process of the Iwate–Miyagi earthquake. This detailed rupture analysis will be useful for modelling future earthquake and policy development for seismic hazard assessment and risk reduction.

In recent years, strong motion simulation techniques have been emerged as efficient and powerful

Table 1. Mainshock parameters of the 2008 Iwate–Miyagi earthquake.

Origin time, location, depth	Size source	Fault plane solution	Reference
23:43:53.2 (GMT), 39.03°N 140.85°E, 12 km	$M_0 = 2.58 \times 10^{19}$ N m, $M_w = 6.9$	NP1: $\phi = 17^\circ$, $\delta = 42^\circ$, $\lambda = 87^\circ$ NP2: $\phi = 201^\circ$, $\delta = 48^\circ$, $\lambda = 92^\circ$	Global CMT Harvard

tools in designing earthquake-resistant structures in seismically active regimes. As a consequence, numerous authors including Miyake *et al.* (1999, 2001, 2003), Kamae and Kawabe (2004), Miyahara and Sasatani (2004), Suzuki and Iwata (2007), Kurahashi and Irikura (2011), Takiguchi *et al.* (2011) and Asano and Iwata (2012) have employed empirical Green's function (EGF) technique to simulate high-frequency records using strong motion generation areas (SMGAs) in the

rupture plane. Although the EGF technique is the most dependable one, the requirement of an after-shock event has created a bottleneck. In the above light, the semi-empirical technique would be of great significance as it does not require aftershock records and utilises empirically generated envelope function to simulate strong motion records (Midorikawa 1993). The efficacy of the above technique has been successfully established for 1985 Central Chile earthquake (M_s 7.8), 1986 Dharmsala (M_s 5.3) and

Figure 1. Processed NS and EW components of observed acceleration records at 16 different stations IWTH25, IWTH26, AKTH04, IWTH24, MYGH02, AKTH06, IWTH20, AKTH19, IWTH05, IWTH04, MYGH04, IWTH19, IWTH22, IWTH27, MYGH11 and IWTH23 used for simulation. Star represents the epicentre of mainshock and the triangles show the location of the stations (map after Suzuki *et al.* 2010).

Figure 2. Spatial distributions of 105 aftershock events recorded on KiK-net, K-NET and USGS network stations. Star represents the mainshock location. Solid circles represent the 105 aftershocks of the event (map after Suzuki *et al.* 2010).

Figure 3. (a) Rupture model in a layered earth medium. Star and triangle denote the nucleation point of identified SMGA and observation point, respectively. (b) Summation of the records from each subfault of SMGA to simulate the acceleration record of the target earthquake.

1991 Uttarkashi earthquake (M_s 6.7). Later on, Joshi *et al.* (2014) modified the semi-empirical technique to consider only SMGAs instead of the whole rupture plane for strong motion simulation. This modification significantly improved the applicability of the semi-empirical technique for the estimation of ground-motion characteristics. In continuation of our growing interest in the modified semi-empirical technique (MSET), we herein

demonstrate the applicability of MSET for the 2008 Iwate–Miyagi earthquake.

2. Motivation

As we previously mentioned the IWTH25 station of KiK-net (National Institute for Educational Development), situated 3 km south-west of the

Figure 4. Flowchart illustrating the methodology for the simulation of strong motion records.

epicentre, observed the largest PGA value during an earthquake. These outcomes inspired us to derive the detailed rupture process of the Iwate–Miyagi earthquake. The above analysis will be useful for the development of a policy for seismic hazard assessment and risk reduction. Furthermore, this will provide an in-depth knowledge on the source characteristics of this earthquake, which will be useful for modelling future earthquakes in this region. To fulfil the above aim, the strong motion records at 16 proximal stations of KiK-net are used to estimate the ground-motion characteristics of the Iwate region. Primarily, this research work has been focused on the reliability of the MSET to estimate the source model of the Iwate–Miyagi earthquake. The simulated records will provide a detailed analysis of regional peculiarities of ground motion excitation and propagation and therefore upgrades the various approaches of seismic hazard analysis.

Figure 5. Plot for duration parameter (T_d) estimated from the acceleration records of the 2008 Iwate–Miyagi earthquake.

3. Data

The 2008 Iwate–Miyagi earthquake was recorded at 655 stations of Kyoshin (K-NET) and Kiban Kyoshin network (KiK-net) installed across Japan. The acceleration data from 16 near-field stations with epicentral distance between 3 and 86 km was used (figure 1). In particular, we employed the strong motion data produced at KiK-net borehole stations, which are less influenced by heterogeneous subsurface structures near the ground surface. Initially, recorded data were processed for instrument scaling. Instrument scaling converts counts/volt recorded by instruments into actual ground motion. Different instruments have different scaling factors and based on the type of sensor, different values of the scaling factor are proposed for different data. In the present study, data recorded by KiK-net borehole stations were corrected with scaling factor 2940/6170270. The other major problem with accelerograms is distortions and shifts of the reference baseline. In the present study, this distortion was removed by applying baseline correction to the recorded data. Finally, to remove low- and high-frequency noise, a fourth-order band pass butterworth filter was applied to the data. Low cut was selected as 0.01 Hz by the visual inspection of the integrated acceleration time series (Boore and Bommer 2005). The high cut was maintained at 10 Hz in view of the range of interest for earthquake-resistant design. The whole

Figure 6. Theoretical (grey) and observed (black) displacement spectra of recorded acceleration (mainshock and aftershock) for NS and EW component at IWTH20 station.

Table 2. Average values of source parameters calculated from source displacement spectra of mainshock and aftershock at IWTH20 station.

	Corner frequency f_c (Hz)	Flat level spectrum Ω_0 (m s)	Seismic moment M_0 (N m)	Stress drop $\Delta\sigma$ (Pa)
Event				
Mainshock	0.195	8.5	2.61×10^{18}	60,97,000
Aftershock	0.5	0.225	6.91×10^{16}	272,000

processing of the recorded data was carried out using the Seismosignal software, Seismosoft (2002).

Along with this mainshock event, we also used a total of 105 aftershock events that were recorded at USGS, K-NET and KiK-net, stations during a 16-day period from 14 June 2008 to 1 July 2008 in the present study (figure 2). The spatio-temporal distribution of these aftershocks revealed an approximate NW trend of the events.

Table 3. Aftershock parameters of the 2008 Iwate–Miyagi earthquake.

Hypocentre	Size	Fault plane solution	Reference
14 June 2008 14:42:34.5 GMT 39.05°N, 140.94°E 17.3 km	$M_o = 1.79 \times 10^{16}$ N m, $M_w = 4.8$	NP1: $\phi = 210^\circ$, $\delta = 34^\circ$, $\lambda = 93^\circ$ NP2: $\phi = 27^\circ$, $\delta = 57^\circ$, $\lambda = 88^\circ$	Global CMT Harvard

Figure 7. Observed (black) and simulated (grey) records at IWTH20 station for different nucleation points. Location of final nucleation point corresponding to minimum RMSE.

Table 4. *Parameters of the SMGA used for final simulation.*

SMGA	SMGA	References
Length (km)	18.0	Wells and Coppersmith (1994)
Width (km)	9.0	Wells and Coppersmith (1994)
No. of subfaults ($N \times N$)	3×3	Scaling relation (Kanamori and Anderson 1975)
Strike	201°	CMT Harvard
Dip	48°	CMT Harvard

4. Methodology

In this study, we employed MSET to simulate strong motion records of the 2008 Iwate–Miyagi earthquake. As we previously mentioned, it is an improved version of the semi-empirical technique pioneered by Midorikawa (1993) to estimate strong motion characteristics. Multiple researchers employed the above technique to simulate strong motion

Figure 8. Source model of the 2008 Iwate–Miyagi earthquake (M_w 6.9) showing one SMGA within the rupture plane. Solid circles show the aftershock distribution within the region. The solid star represents the epicentre of the earthquake and solid triangles indicate the strong motion stations (map after Suzuki *et al.* 2010).

records (Joshi and Patel 1997; Kumar *et al.* 1997; Joshi *et al.* 1999, 2001, 2012a, b, 2014, 2015; Joshi 2001, 2004; Joshi and Midorikawa 2004; Sandeep *et al.* 2014a, b, 2015, 2017a, b, c, 2019; Kumar *et al.* 2016). In this technique, the rupture plane of the target earthquake is divided into grid of equal sizes known as subfaults. It is worth mentioning that the above division follows the self-similarity laws proposed by Aki (1967) which later on were modified by Kanamori and Anderson (1975). For each subfault, Boore (1983) has described the acceleration spectra $A(f, R)$ as follows:

$$A(f, R) = CS(f)D(f)F(f, R), \quad (1)$$

where C is the constant scaling factor; $S(f)$ is the source acceleration spectrum (Brune 1970); $D(f)$ is the

high frequencies attenuation which is mainly controlled by $f_{\max}$ (high-frequency cut-off range of the high-cut filter) and $F(f, R)$ is the attenuation factor (Boore 1983).

To generate the acceleration spectra, Boore (1983) utilised the multiplication of theoretical filters with the spectrum of band-limited finite duration white Gaussian noise. The obtained acceleration spectra for each subfault correspond to the acceleration records in time domain and require further correction for the difference in slip duration of the target and small earthquake (subfaults). As a consequence, the corrected acceleration record $A_{ij}(t)$ is generated by convolving the earlier simulated records $a_{ij}(t)$ with the correction function $F(t)$ (Irikura and Kamae 1994; Irikura *et al.* 1997) and is expressed as

$$A_{ij}(t) = F(t) * a_{ij}(t). \quad (2)$$

Here $F(t)$ stands for the correction function and is represented as

$$F(t) = \delta(t) + [(N - 1)/T_R(1 - \exp(-1))] \times \exp(-t/T_R), \quad (3)$$

where i, j refer to the subfault position along the rupture length and width, respectively, N denotes the total number of subfaults rupture length or width, $\delta(t)$ is the delta function and T_R is the rise time.

Table 5. Velocity model (Ukawa *et al.* 1984) used for studying source model.

Depth (km)	V_s (km/s)	Density (kg/m ³)
0	3.26	2400
2	3.30	2600
6	3.35	2600
10	3.40	2600
14	3.45	2600
10	3.49	2600
12	3.54	2600
14	3.59	2600

Figure 9. Four layer velocity model used for simulation of the Iwate–Miyagi earthquake (Ukawa *et al.* 1984). Rupture with N201°E strike direction and 48° dip is placed in the fourth layer of the medium.

Figure 10. Comparisons of observed (black) and simulated (grey) acceleration records of NS and EW components at (a) IWTH25, IWTH26, AKTH04, IWTH24 and (b) MYGH02, AKTH06, IWTH20 and AKTH19 stations. RMSE shows the root mean square errors of simulated records with observed records.

Figure 11. Comparisons of observed (black) and simulated (grey) acceleration records of NS and EW components at (a) IWTH05, IWTH04, MYGH04, IWTH19 and (b) IWTH22, IWTH27, MYGH11, IWTH23 stations. RMSE shows the root mean square errors of simulated records with observed records.

Figure 12. Comparisons of pseudo-acceleration response spectra calculated from observed (black) and simulated (grey) acceleration record of NS and EW components at (a) IWTH25, IWTH26, AKTH04, IWTH24 and (b) MYGH02, AKTH06, IWTH20 and AKTH19 stations. RMSE shows the root mean square errors of simulated records with observed records.

This semi-empirical technique demands appropriate windowing of the corrected simulated records. Relevant to this, Kameda and Sugito (1978) have proposed the functional form of the acceleration envelope $e_{ij}(t)$ and further modified by Joshi in 2004. Following their modification, the final acceleration record $ac_{ij}(t)$ has been generated by the multiplication of the corrected simulated acceleration record with the envelope function as follows:

$$ac_{ij}(t) = e_{ij}(t) \cdot A_{ij}(t), \quad (4)$$

where $e_{ij}(t)$ is the envelope function and is represented as

$$e_{ij}(t) = T_{ss}(t/T_d) \cdot \exp(1 - t/T_d), \quad (5)$$

where T_d and T_{ss} are the duration parameter and transmission coefficient, respectively.

The summation of all acceleration record $ac_{ij}(t)$ from the individual subfault arriving at an observation point with time shift t_{ij} generates the final simulated acceleration record $Ac(t)$ for the target event as follows:

Figure 13. Comparisons of pseudo-acceleration response spectra calculated from observed (black) and simulated (grey) acceleration record of NS and EW components at (a) IWTH05, IWTH04, MYGH04, IWTH19 and (b) IWTH22, IWTH27, MYGH11, IWTH23 stations. RMSE shows the root mean square errors of simulated records with observed records.

$$Ac(t) = \sum_{i=1}^N \sum_{j=1}^N ac_{ij}(t - t_{ij}). \quad (6)$$

In the MSET, we considered only the contribution of identified SMGA towards strong ground motion instead of the entire rupture plane. In the present study, we modelled an SMGA in the rupture plane of the 2008 Iwate–Miyagi earthquake using

MSET (figure 3). The above methodology is also described in the form of a flowchart (figure 4).

5. Scaling laws

The MSET relies on various region-specific parameters such as the duration parameter (T_d) and the quality factor, $Q(f)$, of the region. The duration

Table 6. Matching details between observed and simulated PGA, and response spectra at different stations.

Station	Epicentral distance (km)	Component of the records	RMSE between simulated and observed PGA records	RMSE between simulated and observed response spectrum
IWITH25	03	NS	0.83	0.95
		EW	0.81	0.92
IWITH26	12	NS	0.80	0.64
		EW	0.92	0.66
AKTH04	22	NS	0.92	0.76
		EW	0.92	0.83
IWITH24	22	NS	0.79	0.71
		EW	0.81	0.73
MYGH02	27	NS	0.73	0.79
		EW	0.71	0.71
AKTH06	34	NS	0.72	0.73
		EW	0.66	0.89
IWITH20	38	NS	0.75	0.90
		EW	0.76	0.81
AKTH19	40	NS	0.81	0.64
		EW	0.73	0.72
IWITH05	45	NS	0.81	0.78
		EW	0.87	0.69
IWITH04	47	NS	0.58	0.74
		EW	0.61	0.75
MYGH04	47	NS	0.82	0.74
		EW	0.88	0.68
IWITH19	49	NS	0.83	0.76
		EW	0.81	0.73
IWITH22	50	NS	0.73	0.71
		EW	0.71	0.69
IWITH27	56	NS	0.74	0.79
		EW	0.68	0.73
MYGH11	70	NS	0.70	0.80
		EW	0.79	0.75
IWITH23	86	NS	0.81	0.81
		EW	0.73	0.74

parameter (as discussed in equation 4) controls the duration of the acceleration envelope and can be calculated using the data recorded in the source area. Midorikawa (1989) suggested a generalised regression relation for the duration parameter and its linear form is given in equations (7a) and (7b):

$$T_d = 0.0015 \times 10^{0.5M} + aR^b, \quad (7a)$$

$$\begin{aligned} \log_{10}(T_d - 0.0015 \times 10^{0.5M}) \\ = b \log_{10}(R) + \log_{10}(a), \end{aligned} \quad (7b)$$

where R is the hypocentral distance in km and M is the moment magnitude of small earthquake. In the

above equation, one part is dependent on the size of the earthquake (M) while the other, on the distance parameter (R). Herein, we used three events (M) 5.7, 5.4 and 5.3 recorded on 10, 6 and 9 stations, respectively, to estimate the coefficients ‘ a ’ (intercept) and ‘ b ’ (slope) as given in equation (7b) and figure 5. The estimated T_d for the 2008 Iwate–Miyagi earthquake is given as

$$T_d = 0.0015 \times 10^{0.5M} + 1.73R^{0.26}. \quad (8)$$

As far as the quality factor is taken into account, Kiyono (1992) described an average relation of the quality factor $Q(f)$ as $158f^{0.7}$ for the Japan region. This relation has been successfully verified by Joshi and Midorikawa (2004) and therefore will be used here.

Figure 14. (a) Parametric comparison of NS and EW components of observed and simulated PGA and (b) plot of NS and EW components of observed and simulated PGA with respect to epicentral distance (R) at IWTH25, IWTH26, AKTH04, IWTH24, MYGH02, AKTH06, IWTH20, AKTH19, IWTH05, IWTH04, MYGH04, IWTH19, IWTH22, IWTH27, MYGH11, IWTH23 stations. Black and grey lines show the attenuation characteristics of observed and simulated PGA values with epicentral distance R .

6. Rupture model

A primary component of the rupture model is to determine the dimensions of the rupture plane. In this context, the widely known Wells and Copper-smith (1994) relation is implemented to estimate the length and width of the rupture plane and calculated as 40 and 18 km, respectively. Notably, the estimated rupture dimensions are in good agreement with Suzuki *et al.* (2010) and Hikima *et al.* (2008). Next, the strike, dip angle and depth of the rupture plane are determined by the Global CMT Harvard (available online, www.globalcmt.org) and found to be N201°E, 48° and 12 km, respectively. On the basis of mainshock location and spatio-temporal distribution of aftershocks of this earthquake, the possible location

of the rupture plane is estimated. Suzuki *et al.* (2010) have suggested a westward dipping plane for this earthquake. Recorded data for this earthquake suggests that the duration of a strong ground motion is surely less than expected. The duration of a high-frequency ground motion at one of the proximal stations, IWTH25 is about 7.1 s. The rupture velocity of 2.87 km/s for a 40-km rupture length suggests the total duration of strong motion record as 13.94 s. This unexpected small duration of strong motion record leads to the conclusion that only a small patch instead of the whole rupture plane is attributed to generate strong ground motion. Therefore, the present study describes the modelling of a small patch having an area of $18 \times 9 \text{ km}^2$ within the rupture plane. This small patch is termed as SMGA and requires several

parameters for modelling. Source displacement spectrum is used to calculate the SMGA parameters. A comparison between the observed and theoretical displacement spectrum of the recognised SMGAs in mainshock and aftershock at IWTH20 is illustrated in figure 6. Table 2 describes the estimated SMGA parameters from displacement spectra matching. As both the mainshock and aftershock recorded phases are clearly identifiable for IWTH20 station and they are considered for analysis.

Relying on the self-similarity relations of Kanamori and Anderson (1975), the rupture plane of SMGA is divided into 3×3 grids. For scaling, we considered one of the aftershock events (M_w 4.8) as subfault (table 3). Based on the surface offset along a fault, the background seismicity of the region or the slip rate from GPS observations high slip rate area on the fault plane can be identified (Irikura and Miyake 2011). Furthermore, SMGA is identified on the basis of aftershock clusters in the rupture plane. Next, the proper selection of the nucleation point in the proposed SMGA is an important and challenging task. For this purpose, all possible positions of nucleation point are assumed in the SMGA. On the basis of minimum RMSE of waveform comparison at IWTH20 station, we confirm the nucleation point in the extreme western corner of the SMGA which agreed well with Suzuki's (2010) suggestion of a westward dipping plane for this earthquake (figure 7). Moreover, the identified location of the nucleation point also justifies Kato's (2012) suggestion where he proposed that stress found to be concentrated near the deeper edge of the plane and when it exceeds the fracture energy, rupture propagates. The estimated parameters of SMGA are summarised in table 4 and the final estimated rupture model with SMGA is shown in figure 8. The velocity model of Ukawa *et al.* (1984) is used (table 5) and the rupture is positioned in the fourth layer of the velocity model at a depth of 12 km (figure 9).

7. Strong motion simulation of the 2008 Iwate–Miyagi earthquake

Strong motion records were simulated at 16 near-field stations using estimated SMGA parameters and MSET (figures 10 and 11). Furthermore, pseudo-acceleration spectra were obtained from the simulated and observed acceleration records with 5% damping (figures 12 and 13). A comparable match between

simulated and observed data was found for all stations except a few ones. This may be due to the factors like local inhomogeneities, frequency-based attenuation of the energy. A brief comparison between simulated and observed records is summarised in table 6. A variation of simulated and observed PGA and its attenuation with epicentral distance is shown in figure 14.

8. Discussion

As we mentioned earlier, the intriguing basis of the 2008 Iwate–Miyagi earthquake was the largest PGA observed at IWTH25 station. Therefore, the relationship between the rupture process and recorded PGA values is a matter of significant attention. This analysis reveals that the highest PGA phase occurs during the initial 2–3 s of the total record duration at IWTH25 station. This suggests that the particular phase is generated from a patch on the rupture plane that is the first to rupture. This patch with a high slip rate is referred to as SMGA and is identified just below IWTH25 station. This evidence highly supports our estimated source model using MSET.

9. Conclusions and future scope

We estimated the source model of the 2008 Iwate–Miyagi (M_w 6.9) earthquake using MSET. The technique provides one SMGA in the rupture plane and nucleation point in the extreme western corner of SMGA. Using estimated rupture plane with one SMGA strong motion records are simulated at 16 proximal stations. A similar match between the simulated and observed waveforms in both the frequency and time domains is observed. The quantitative analysis suggests an almost linear fit for PGA values of these waveforms. Moreover, the attenuation rate of these PGA values with epicentral distance follows the similar trend. These results confirm the reliability of MSET and estimated source model of this earthquake. Therefore, we believe that the present study will be highly useful for seismic hazards analysis and modelling future earthquakes in this region.

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