Characterized Source Model of The 2013 Lushan Earthquake (Mw 6.6) by Empirical Green's Function Method

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Abstract

Ground motions near the source area of the mainshock of the 2013 Lushan earthquake (M_w 6.6) in the Sichuan Province in China were reproduced using the characterized source model and the empirical Green's function method (EGFM). The best-fit characterized source model consists of one strong motion generation area (SMGA) and a background area. The synthesized ground motions of the characterized source model were in fairly good agreement with the observed ones in the frequency range from 0.5 to 30.0 Hz at eleven strong-motion stations. The relationships between the SMGA and the seismic moment, and those between the flat amplitude of acceleration source spectrum in the short-period and the seismic moment, for the 2013 Lushan earthquake (M_w 6.6), almost followed the empirical scaling relationships of inner fault parameters so far developed for the crustal earthquakes. The reason for the largest PGA ($>1g$) in the strong-motion observation history of China recorded at the 051BXD strong-motion station was investigated from the source and site effects. Through comparing the synthesized ground motions at the station for three different rupture-starting-point and comparing the earthquake H/V spectral ratios between the mainshock and the EGF event, neither the significant directivity effect nor the strong nonlinear effect was observed on the ground motions at the 051BXD. The predominant period around 0.1 s of the Fourier spectra of both the mainshock and the EGF event suggested that the site effect should be responsible for the large record.

Introduction

The 2013 Lushan earthquake (M_w 6.6) struck the Lushan county, Ya'an city, Sichuan province in China at 08:02 (Beijing time) on April 20, 2013. The mainshock caused much damage of buildings, 196 people dead and 21 people missing. The strong ground motions during the mainshock of the 2013 Lushan earthquake were recorded by as many as 114 strong-motion stations including some near-fault stations as shown in Figure 1. The largest PGA was 1005 cm/s^2 in the east-west (EW) component at 051BXD station approximately 16 km far away from the epicenter, which was the first time of exceeding $1g$ in the strong-motion observation history of China. It is important to clarify the source and site effects to interpret the large record.

To date, the source rupture process of this earthquake has been illuminated by many kinematic source models developed with the waveform inversion method using teleseismic data (Liu et al. 2013), joint inversion of strong-motion data and teleseismic data (Hao et al. 2013; Zhang et al. 2014), and joint inversion of strong-motion data, teleseismic data and GPS records (Li et al. 2017). Despite of the different data sets and methods, these kinematic source models were almost in common that the mainshock ruptured a blind thrust fault in the southern part of the Longmen Shan fault belt, and that the large slip areas surrounded the hypocenter. The synthesized ground motions using these inverted source models agreed well with the long-period (e.g., $>1 \text{ s}$) observed ground motions, whereas they cannot match the observed ground motions at near-source stations in the period range of engineering interests (e.g., $0.1 \sim 10.0 \text{ s}$). Then, the characterized source model consisting of several asperities and a background area in

the seismogenic zone was applied to synthesize the ground motions. This model involves the outer and inner fault parameters. The outer fault parameters are defined to outline the overall picture of the target earthquake such as entire source area and seismic moment, while the inner fault parameters are defined by asperities with large slips and stress drops. Strong ground motions of engineering interests are mostly generated from the asperities. Therefore, the asperities are called strong motion generation areas (SMGAs). The outer and inner fault parameters follow specific scaling relationships for crustal earthquakes, respectively (Somerville et al. 1999; Dan et al. 2001; Irikura and Miyake 2001, 2011; Miyake et al. 2003; Miyakoshi et al. 2020). However, the empirical scaling relationships of inner fault parameters for the crustal earthquakes in China have not been adequately investigated.

In this study, we elaborate the process to construct the characterized source model of the mainshock with the empirical Green's function method (EGFM) (Irikura 1986), and then examine whether the inner fault parameters of the mainshock agree with the empirical scaling relationships so far developed. Finally, we quantitatively discuss the source and site effects on the large record ($PGA > 1g$) at the 051BXD station.

Methodology

Methodology

The empirical Green's function method (EGFM) was firstly proposed by Hartzell (1978) and then revised by Kanamori (1979) and Irikura (1983, 1986). The ground motions of large event are expressed as a superposition of the ground motions of a small event in Eq. (1)-(3) (Irikura 1986).

$$U(t) = \sum_{i=1}^N \sum_{j=1}^N \frac{r}{r_{ij}} F(t - t_{ij}) * (C \cdot u(t)).$$

1

$$t_{ij} = \frac{r_{ij} - r_o}{V_s} + \frac{\xi_{ij}}{V_r},$$

2

$$F(t) = \delta(t) + \frac{1}{n' (1 - 1/e)} \cdot \sum_{k=1}^{(N-1)n'} \left[\exp\left\{ \frac{-(k-1)}{(N-1)n'} \right\} \cdot \delta\left\{ t - \frac{(k-1)\Gamma}{(N-1)n'} \right\} \right].$$

3

Where $U(t)$ represents the ground motions of large event, and $u(t)$ the ground motions of small event regarded as the empirical Green's functions (EGF). The subscripts i and j are indices increasing along the strike and dip directions respectively. The terms r , r_{ij} and r_0 are the respective distances from the station to the hypocenter of the small event, from the station to the (i,j) subfault, and from the station to the rupture starting point on the fault plane of the large event. ξ_{ij} is the distance between the rupture starting point and the (i,j) subfault. V_s and V_r are the S-wave velocities in the source region and rupture velocity on the fault plane, respectively. $F(t)$ is the correction function of slip velocity between large and small events which was modified by Irikura et al. (1997). The parameters, N and C , are the ratios of fault sizes (length and width) and stress drops between the large and small events, respectively. n' is the division number to shift the artificial periodicity to a frequency higher than that of interests, e Euler's number, and Γ the rise time of the large event.

The formulation of EGFM in Eq. (1) implies that the synthesized ground motions only consider the contribution of the Green's functions from the far-field term. Because the empirical Green's functions contain the contributions of near-, intermediate- and far-field terms, the synthesized ground motions naturally contain the contributions from all terms. According to Nozu et al. (2006), the Fourier spectral ratio of total waves corresponding to near-, intermediate- and far-field terms to far-field S-wave term approaches to 1 when the normalized frequency ($=2\pi fr/V_s$, r is the hypocentral distance) is larger than 8. It means that the contributions of the near-, intermediate-field term can be neglected if only $f > 8V_s/2\pi r$. As the V_s in the source region is 3.50 km/s (Han et al. 2014), and the shortest hypocentral distance is approximately 20 km, the far-field S-wave term in the synthesized ground motions is comparable with that of the total terms without any corrections at frequencies larger than 0.2 Hz.

We adopted the method proposed by Miyake et al. (1999) to estimate the fault size of the EGF event, N and C by fitting the theoretical source spectral ratio to the observed one. The observed source spectral ratio is estimated from the ratio of observed Fourier spectrum (vector summation of two horizontal components) removing the path effect between large and small events, while the theoretical source spectral ratio is expressed as Eq. (4).

$$SSRF(f) = \frac{M_o}{m_o} \frac{1 + (f/f_{ca})^2}{1 + (f/f_{cm})^2},$$

4

where M_o and m_o are the seismic moment of large and small events respectively, and f_{ca} and f_{cm} are the corner frequencies of large and small events, respectively.

Once the best-fit theoretical source spectral ratio is determined by searching the minimum of weighted least squares (Miyake et al. 2013), the corner frequencies- f_{ca} and f_{cm} are directly obtained according to

Eq. (4). The proportional parameters, N and C , are estimated from Eq. (5). The fault size r_a and stress drop $\Delta\sigma_a$ of the EGF event are estimated by applying Eq. (6) (Eshelby, 1957; Brune, 1970, 1971).

$$N = \frac{f_{ca}}{f_{cm}}, C = \left(\frac{M_o}{m_o} \right) \left(\frac{f_{cm}}{f_{ca}} \right)^3.$$

5

$$r_a = \frac{2.34 V_s}{2\pi f_{ca}}, \Delta\sigma_a = \frac{7}{16} \frac{m_o}{r_a^3}.$$

6

Considering the variability of observed source spectral ratio, the parameters- C , N , r_a , evaluated from Eq. (5)-(6) are not necessarily suitable for synthesizing ground motions. We kept the size of small event- r_a to be constant, and searched the optimal values of C , N , the position indices (i, j) of rupture starting point within the SMGAs, V_r and Γ by applying the adaptive simulated annealing (ASA) algorithm which employs a more efficient sampling of the parameter space than conventional simulated annealing algorithm. We gave a brief introduction about ASA algorithm by referring to Satoh, et al. (2006).

Let $\mathbf{x}(t)$ be the vector composed of parameters $x_i(t)$ (i.e., C , N , i , j , V_r and Γ). $x_i(t)$ is generated from the generating function by use of random variable Δx_i as expressed in Eq. (7). Δx_i is generated from the generating temperature $T_{i,gen}$ and uniform random value u as expressed in Eq. (8).

$$x_i(t) = x_i(t-1) + (B_i - A_i) \Delta x_i, x_i \in [A_i, B_i].$$

7

$$\Delta x_i = \text{sgn} \left(u_i - \frac{1}{2} \right) T_{i,gen}.$$

$$\left[(1 + 1/T_{i,gen})^{|2u_i-1|} - 1 \right], \Delta x_i \in [-1, 1],$$

8

where $T_{i,gen}$ is calculated from the temperature reduction function as

$$T_{i,gen}(k_i) = T_{i,gen}(0) \exp(-c_i k_i^\alpha),$$

9

where k is an annealing factor for each generating temperature, c is a constant defining the relative width of the generating distributions, a is a factor associated with the speed of temperature decreasing. The values of the parameters- $T_{i,gen}(0)$, c , a are set to 1.0, 1, 0.6, respectively, after several numerical experiments.

Once new values for $\mathbf{x}(t)$ are generated, the difference of the misfit functions between new and previous is computed as

$$\Delta E = E(\mathbf{x}(t)) - E(\mathbf{x}(t-1)),$$

10

where $E(\mathbf{x})$ is the misfit function defined by the residual between synthesized and observed records for acceleration envelopes and displacement waveforms (Miyake et al. 1999).

The new values $\mathbf{x}(t)$ are accepted if $\Delta E < 0$. If $\Delta E > 0$, $\mathbf{x}(t)$ are accepted if the uniform random value u is less than P which is expressed as Eq. (11).

$$P = \exp \left(- \frac{\Delta E}{T(k)} \right),$$

11

where the acceptance temperature is calculated as Eq. (9).

Determination of parameters required for the EGF

The characterized source model in this study is composed of a strong motion generation area (SMGA) consisting of $N \times N$ subfaults along the strike and dip directions, and a background area in the seismogenic zone on the fault plane. Because the background area is mostly contributable to the long-period strong ground motions (Kurahashi and Irikura 2010), we estimated the strong ground motions only from the contribution of SMGA neglecting the contributions from the background area. The number of SMGAs generally depends on the complexity of the source rupture process. For large magnitude earthquakes, plural SMGAs seem to distribute randomly (e. g. Kamae and Irikura 1998; Kurahashi and Irikura 2010, 2013). For the 2013 Lushan earthquake, several source-rupture-process studies based on the waveform inversion analyses were common in that the large slip area concentrated around the hypocenter. Therefore, it is reasonable to suppose that one SMGA located in the large slip area of the kinematic source models is suitable for synthesizing the ground motions.

First, we selected an aftershock with M_w 4.3 as an EGF. The aftershock occurred near the SMGA on 22:16, April 21, 2013 (Beijing time) and had a similar source mechanism (Yi et al. 2013) with the mainshock. The positions of hypocenters and source mechanisms for the mainshock and this aftershock are listed in Table 1. The dip and rake angles of the aftershock are not completely identical to those of the mainshock. However, it is acceptable as the propagation paths and site effects are more influential on the

mainshock ground motions in a shorter period range of engineering interest than the source effects. Figure 1 shows the distribution of strong-motion stations and beach ball diagrams of source mechanisms for the mainshock and the EGF event. Figure 1 also shows the projection of the kinematic source model with a large rectangular. The kinematic source model developed by waveform inversion method (Li et al. 2017) is adopted for constructing the characterized source model as the hypocenter is close to the position determined by high-resolution relocation (Han et al. 2014). The ground motions of the M_w 4.3 aftershock at the stations where the records of both the mainshock and the EGF event were available are regarded as EGFs. We synthesized ground motions at eight strong-motion stations (e.g., 051BXD, 051BXZ, 051BXM, 051BXY, 051QLY, 051YAM, 051PJD, 051YAD) surrounding the source region applying the EGF method.

Table 1
Information of the mainshock (Li et al., 2017) and the EGF event.

Origin time (Beijing time)	2013/04/20, 08:02	2013/04/21, 22:16
Latitude, Longitude	30.284, 102.956	30.339, 102.925*
Depth (km)	15	17.126*
M_w	6.6	4.32**
M_0 (N·m)	1.01×10^{19}	3.80×10^{15} **
Strike/dip/rake	214.0/38.0/103.0	235.0/61.0/106.0**
* refers to Han et al. 2014		
** refers to Yi et al. 2013		

Second, we estimated the inner fault parameters related to the SMGA from the source spectral ratios of the mainshock ground motions to the EGF ones. We employed the S-wave portion with a length of 40.96 s of the mainshock and EGF event to calculate the observed Fourier spectra, and then removed the path effect ($Q_s(f)=155f^{0.6804}$, Tao et al. 2016) from the Fourier spectra to obtain the observed source spectra. The average source spectral ratios and standard deviations for the target stations are shown with thick gray and dashed curves in Figure 2. Due to the known moment magnitudes of the mainshock and EGF events, the maximum amplitude of the theoretical source spectral ratio could be fixed at M_0/m_0 . The theoretical source spectral ratios were estimated by assigning the corner frequencies of the mainshock and the EGF events, respectively. We set the lower limit frequency for fitting the observed source spectral ratio to be 0.5 Hz considering the low signal-to-noise ratio of observed ground motions, and we set the upper limit frequency to be 30.0 Hz which was usually used for the Fourier transformation analysis of strong-motion records in China (Dai et al. 2013; Wen et al. 2015). We determined the best fitting of the theoretical source spectral ratio (red curves in Figure 2) to the average observed one (thick curves in Figure 2) in the frequency range of 0.5 to 30.0 Hz when $f_{ca}=1.90$ Hz and $f_{cm}=0.17$ Hz. Subsequently, we applied Eqs. (5-6) to calculate $N=11$, $C=2.12$, $r_a=0.68$ km, and $\Delta\sigma_a=4.85$ MPa. For small or moderate

earthquakes, the fault length can be identical with the fault width, thus the fault length or width of the EGF event is $\sqrt{\pi r_a}=1.21$ km.

Third, we applied the ASA algorithm to determine the optimal values of the parameters required by the EGFM, such as C , N , i , j , V_r and Γ . We fixed the rupture starting point at the hypocenter (Li et al. 2017) and kept the size of fault length/width of the EGF event to be constant. Under the same acceptance temperature, the iteration of the ASA algorithm is carried out 5 times, and the search of indices (i , j) of the rupture starting point is carried out 10 times for each iteration, whereas the final value of k is set to 100. Therefore, the optimal parameters are determined when the misfit function reaches the global minimum among the 5000 iterations. Table 2 lists the search range for each parameter in the second column. The search ranges for V_r and rise time- τ_a of the EGF event ($\Gamma = N\tau_a$ for the mainshock) are roughly assigned, while the upper and lower limits for C and N are evaluated by the fitting of the theoretical source spectral ratio to the observed ones as shown in dashed curves that are one standard deviation over and below the log average observed source spectral ratio. In accordance with the fitting frequency range of the observed source spectral ratio, we applied a bandpass filter of 0.5-30.0 Hz beforehand to the waveforms with a time window of 30 s which contains the S-wave portions at the eight target stations. Because step-like pulses were observed on the baseline of the records in the EW component at the 051QLY station for both the EGF event and mainshock, we abandoned to synthesize the ground motions in the EW component to eliminate the special process of baseline correction.

Table 2
Parameters related to synthesize ground motions by EGFM

Parameters	Search ranges	Determined values
Rupture velocity (km/s)	$(0.55\sim0.95)*V_s$	2.68
Rise time (s) for the EGF event	0.01~0.20	0.06*
C	1.28~3.87	2.49
N	9~13	9
Indices of rupture starting point	$(1\sim N, 1\sim N)$	(5, 4)
*Rise time for the mainshock $\Gamma = N\tau_a = 0.54$ s.		

Synthesized ground motions using the characterized source model

We obtained the best-fit SMGA of the characterized source model when the residuals between synthesized and observed records for the misfit function consisting of acceleration envelopes and displacement waveforms (Miyake et al. 1999) reached the global minimum throughout all iterations. The optimal values of the parameters, such as C , N , i , j , V_r and Γ , are listed in the third column in Table 2. The SMGA is 118.6km^2 (10.89×10.89 km), the stress drop is 12.0 MPa, and the seismic moment of SMGA is

6.37×10^{18} N·m. The location of the SMGA as shown in Figure 3 nearly coincides with the large slip area of the inverted kinematic source model (Li et al. 2017), which suggests that the SMGA can be regarded as equivalent to an asperity. Figure 4 shows the comparisons of waveforms between synthesized and observed acceleration, velocity and displacement in the NS and EW components at eight target stations. Figure 5 shows the comparisons of the Fourier spectra between synthesized and observed ground motions. The Fourier spectra are smoothed by use of a logarithmic window function with a band width parameter ($b=50$) (Konno and Omachi 1998). Overall, not only the waveforms but also the Fourier spectra of the synthesized ground motions are in fairly good agreement with the counterparts of the observed ground motions at the target stations except some stations where synthesized acceleration waveforms are overestimated as nonlinearity of surface geology is not included in the EGFM. We also applied the same set of parameters of the best-fit SMGA to synthesize the ground motions at three non-target stations, i.e. 051PJW, 051CDZ, and 051DJZ where the observed ground motions are not considered in the above inversion analysis. The good consistency between the synthesized and observed ground motions is confirmed (Figure S1 and S2), which further suggests that the characterized source model consisting of one SMGA is suitable for synthesizing the ground motions of the mainshock.

Subsequently, we examined the effectiveness of the inner fault parameters, such as SMGA and acceleration level in the best-fit source model. Here, the SMGA is considered equivalent to the combined area of asperity. Figure 6 shows that the empirical scaling relationship between the combined area of asperities with large slips estimated from waveform inversions for long-period (>1.0 s) motion and the seismic moment (M_o) proposed by Somerville et al. (1999) and Irikura and Miyake (2001, 2011) in the left panel, and the scaling relationship between the flat amplitude of acceleration source spectrum in the short-period (A_0) and M_o proposed by Dan et al. (2001) in the right panel. The relationship between the SMGA and M_o , and the relationship between the A_0 and M_o of the best-fit characterized source model during the 2013 Lushan earthquake (M_w 6.6) are found to be similar to these two empirical scaling relationships. Furthermore, we added the results of the SMGAs of the 2008 Wenchuan earthquake (M_w 7.9) (Kurahashi and Irikura 2010) and those of the 2014 Ludian earthquake (M_w 6.1) (Wang et al. 2017), and the 2017 Jiuzhaigou earthquake (M_w 6.5) (Wu et al. 2020), as shown with square, diamond and solid circle, respectively, in Figure 6. It should be noted that Kurahashi and Irikura (2010) constructed the characterized source model only in the southern part of the fault model, the seismic moment in the southern part was assumed to be half of the seismic moment for the entire fault. The relationships between the SMGAs and M_o for these crustal earthquakes in China agree well with the empirical scaling relationship (Somerville et al. 1999; Irikura and Miyake 2001, 2011; Miyake et al. 2003; Miyakoshi et al. 2020). The A_0 s for the 2014 Ludian earthquake and the 2008 Wenchuan earthquake are a bit larger than the values estimated from the empirical scaling relation, whereas it is acceptable as the values fall in the range indicating factors of 1/2 and 2 for the average (shown in dotted lines). Therefore, the relationships between the A_0 and M_o for these crustal earthquakes also follow the empirical scaling relationship (Dan et al. 2001). It implies that the empirical scaling relationships of inner fault parameters might be applicable to estimate the inner fault parameters for the future crustal earthquakes in China. More inner

fault parameters of the characterized source models for crustal earthquakes in China (if any) are required to investigate the applicability of the empirical scaling relationships.

Discussions

The EGFM is applicable for synthesizing the ground motions on the premise of linear superposition of the EGF, while the nonlinear effects on the ground motions are excluded for applying the EGFM. To examine the influence of nonlinearity on surface geology of observed ground motions, we compared the earthquake H/V spectral ratios of the mainshock with that of the EGF event at eight target stations in Figure 7. The Fourier spectra in three components are calculated from the S-wave portions with a time length of 20.48 s, and then the H/V spectral ratios are evaluated following the method of Kawase et al. (2011). The degree of nonlinearity (DNL) (Noguchi and Sasatani 2008) at each station is evaluated to represent the extent of nonlinear effect. Large DNL suggests strong nonlinear effect, and vice versa. The similarity of the earthquake H/V spectral ratios between the mainshock and the EGF event and the small values of DNLs indicate that nonlinear effects are sufficiently weak at target stations except 051BXZ. Although the observed PGA of the mainshock is quite large at the 051BXD station, the smallest DNL there suggests that the nonlinear behavior of the site is negligible. It is consistent with the fact that the site condition is rock, and the field survey also reported that the station was located on the slope of a small rock hill (Wen and Ren 2014). Conversely, despite of the rock site, strong nonlinear behavior is observed at the 051BXZ station. The cause of nonlinear effect on the station is not clear, as there are no boring data or field survey reports. The synthesized acceleration ground motions are quite larger than the observed ones at the 051BXZ station due to the linear premise of the EGFM. The synthesis through EGFM taking the nonlinear effect into account could be accomplished by introducing certain parameters (Nozu and Morikawa 2003), which is beyond the scope of this study.

The largest PGA was observed in the EW component at the 051BXD station during the mainshock. This observed PGA is remarkably larger than the one predicted by the ground motion prediction equation (GMPE) (Zhao et al. 2016) as shown in Figure 8. We investigated the possible directivity effect on the ground motions in the EW component at the 051BXD and 051YAM stations by comparing the synthesized ground motions for different rupture-starting-points: hypocenter (best-fit SMGA), top of the SMGA (Model A), and bottom of the SMGA (Model B) as illustrated in Figure 9. Figures 10 and 11 show the results of waveforms and acceleration Fourier spectra in the EW component for the above three models, as well as the observed results during the mainshock, at the 051BXD and 051YAM stations. The amplitude of acceleration Fourier spectrum of the synthesized ground motion at the 051BXD station for Model A is similar to that for Model B at periods below 0.3 s. It suggests that the directivity has little effect on the short-period ground motions. On the other hand, the amplitude of acceleration Fourier spectrum of the synthesized ground motion at the 051BXD station for Model A is larger than that for Model B at periods of 1.0 ~ 2.0 s. It indicates that the directivity affects the long-period ground motions at the 051BXD station which is in the forward direction of rupture propagation (Model A). Meanwhile, the synthesized waveforms of Model A are in better agreement with the observed waveforms than those of the best-fit characterized source model. However, if we compare the synthesized ground motions with the

observed ones at other stations, e.g., 051YAM, as shown in Figure 11, the synthesized ground motions of Model A reach a less agreement with the observed ones than those of the best-fit SMGA model. In terms of the fitting of the synthesized ground motions at all target stations, the best-fit SMGA source model is the preferred one among three models. In addition, the amplitude of acceleration Fourier spectrum of Model A is quite larger at periods of 1.0 ~ 2.0 s than that of other two models. It indicates that the directivity effect is noticeable at the 051YAM station which is in the forward direction of rupture propagation (Model B). In contrast, the directivity effect is not significant at the 051BXD station even though the station is located in the forward direction of rupture propagation (Model A). It is because the SMGA dips towards the southwest, the distances between each subfault of the SMGA and the 051BXD station are not so variant when the rupture propagates towards the 051BXD station. We further concluded that the directivity effect could not be responsible for the largest PGA in the EW component at the 051BXD station for the best-fit SMGA source model of which the rupture starting point is close to the center of SMGA.

The synthesized ground motions for the best-fit SMGA of characterized source model have an agreement with the observed ground motions in the EW component during the mainshock as shown in Figure 12. The large PGA can be attributed to the large peak of the Fourier spectrum around 0.1 s during the mainshock. As the acceleration Fourier spectra of both the mainshock and the EGF event predominate near 0.1 s, and strong nonlinear effect is not observed, the site effect at the 051BXD station should be responsible for the large PGA.

Conclusions

We successfully reproduced the ground motions for the mainshock during the 2013 Lushan earthquake (M_w 6.6) using the characterized source model and the empirical Green's function method (EGFM). The source parameters of the best-fit source model are determined by applying the adaptive simulated annealing (ASA) algorithm (Sato 2006) for the misfit function by Miyake et al. (1999) using the waveforms in a frequency range from 0.5 to 30.0 Hz at eight near-source strong-motion stations. The best-fit characterized source model consists of one strong motion generation area (SMGA) and a background area. We also confirmed the good consistency between the synthesized and observed ground motions at other three strong-motion stations where the observed ground motions were not used for the inversion analysis, when the same set of parameters was employed to synthesize the ground motions there.

We found the relationships between the SMGA and M_o , and the relationships between the flat amplitude of acceleration source spectrum in the short-period and M_o , for the characterized source model of the 2013 Lushan earthquake (M_w 6.6), together with the 2014 Ludian earthquake (M_w 6.1), the 2017 Jiuzhaigou earthquake (M_w 6.5) and the 2008 Wenchuan earthquake (M_w 7.9), followed the empirical scaling relationships of inner fault parameters (e.g., Irikura and Miyake 2001; 2011). It implied that the

empirical scaling relationships of inner fault parameters might be applicable for the prediction of strong ground motions for the future crustal earthquakes in China.

The largest PGA during this earthquake was larger than 1g at the 051BXD station where was obtained the first time large strong motions exceeding 1g in the observation history of China. We investigated the site and source effects on the large record at the 051BXD station. The strong nonlinear effect was not observed there by comparing the earthquake H/V spectral ratios between the mainshock and the EGF event. The Fourier spectra of the observed ground motions of both the mainshock and EGF event were dominated in the same short-period range (e.g., 0.1 ~ 0.2 s) which was responsible for the largest PGA. It suggested that the site effect should be responsible for the large record at the 051BXD station. We discussed the influence of the directivity effect on the ground motions in the EW component at the 051BXD station by comparing synthesized ground motions from different rupture-starting-point. Little directivity effect was found from the Fourier spectra of the synthesized ground motions in the short-period range (e.g., 0.1 ~ 0.2 s), which suggested that the directivity effect cannot be responsible for the largest PGA.

Abbreviations

- ASA
adaptive simulated annealing
- EGF
empirical Green’s function
- EGFM
empirical Green’s function method
- DNL
Degree of nonlinearity
- PGA
peak ground acceleration
- SMGA
strong motion generation area

Declarations

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

HW designed the study, analyzed data and drafted the manuscript. KI designed the study, participated in discussions, and interpreted the results. KM and KS contributed to discussions of the data processing and the results. All authors read and approved the final manuscript.

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References

Figures

Figure 1

Distributions of strong-motion stations during the mainshock (M_w 6.6) and the EGF event (M_w 4.3). The large rectangular denotes the projection of the kinematic source model (Li et al. 2017), of which the thick line part denotes the top edge of the fault. Squares and triangles represent the strong-motions stations deployed on the rock and soil sites, respectively, during the mainshock. Solid red circles denote the strong-motion stations during the aftershock. Gray lines are fault traces (Deng et al. 2003) in the studied area.

Figure 2

Fitting of the log average observed source spectral ratio (thick curve). Gray curves are the observed source spectral ratios at the strong-motion stations. Dashed curves are the log standard deviation above and beneath the log average observed source spectral ratios. Red curve is the best-fitting theoretical source spectral ratio in the frequency range of 0.50 ~ 30.0 Hz.

Figure 3

Slip distribution of the kinematic source model (Li et al. 2017) drawn with colors and a rectangular of the best-fit SMGA of the characterized source model. The star and inverse triangle denote the epicenter of the mainshock and the EGF event, respectively.

Figure 4

Comparison of the observed ground motions (acceleration, velocity, displacement) (black) in the NS and EW components with the synthesized ground motions (red). The ground motions only in the NS component are estimated at 051QLY station.

Figure 5

Comparison of the Fourier spectra (black) of the observed ground motions with those of the synthesized ground motions (red). The Fourier spectra are the vector summation in two horizontal components at stations except 051QLY of which the Fourier spectrum is evaluated from the ground motions only in the NS component. The Fourier spectra are smoothed by use of a logarithmic window function (Konno and Omachi, 1998).

Figure 6

Empirical scaling relationships of inner fault parameters between the combined area of asperities and the seismic moment (left), and between the flat amplitude of acceleration source spectrum in the short period and the seismic moment (right). The thick lines represent the regression equations derived by Somerville et al. (1999) in the left panel and by Dan et al. (2001) in the right panel. The dashed lines are extrapolation of regress equations. The dotted lines denote the factors of 1/2 and 0.5 for the average.

Figure 7

Comparison of the earthquake H/V spectral ratios between the mainshock (red) and the EGF event (black). The degree of nonlinearity (DNL) is shown in the left-bottom of each panel.

Figure 8

Ground motion prediction equation (GMPE) for M_w 6.6 earthquake of the shallow crustal earthquakes (Zhao et al. 2016) and observed PGAs at 5 near-source stations of the mainshock. The solid line denotes the GMPE of rock sites where the natural periods (e.g., predominant period of earthquake H/V spectral ratio for the EGF event) are smaller than 0.2 s, and the dashed lines the standard deviation. The circle denotes the observed PGA (geometric average of PGAs in two horizontal components) for the mainshock. The closest distance between the SMGA and the station is taken as the fault distance.

Figure 9

Geometrical relation between the best-fit SMGA and two strong-motion stations (051BXD and 051YAM). The star denotes the epicenter of the mainshock. The red, blue and purple diamonds denote the positions of the rupture starting points for the best-fit SMGA, Model A, Model B, respectively.

Figure 10

Left: Observed and synthesized waveforms (acceleration, velocity and displacement) for three models in the EW component at the 051BXD station. Black, red, blue, and purple represent observed, best-fit model, Model A and Model B, respectively. Right: Acceleration Fourier spectra between the observed and synthesized ground motions of three models in the EW component at the 051BXD station during the

mainshock. The Fourier spectra are smoothed by use of a logarithmic window function (Konno and Omachi 1998).

Figure 11

Waveforms and acceleration Fourier spectra between the observed and synthesized ground motions in the EW component at the 051YAM station during the mainshock. The legends are referred to Figure 10.

Figure 12

Observed and synthesized acceleration Fourier spectra in the EW component at the 051BXD station. The black, red, and thin lines denote the acceleration Fourier spectra for the observed and synthesized ground motions of the best-fit characterized source model, and the observed ground motions of the EGF event, respectively. The Fourier spectra are smoothed by use of a logarithmic window function (Konno and Omachi 1998).

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