Strong ground motion simulation for the 2013 Lushan $M_w6.6$ earthquake, Sichuan, China, based on the inverted and synthetic slip models

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Abstract It is well known that quantitative estimation of slip distributions on fault plane is one of the most important issues for earthquake source inversion related to the fault rupture process. The characteristics of slip distribution on the main fault play a fundamental role to control strong ground motion pattern. A large amount of works have also suggested that variable slip models inverted from longer period ground motion recordings are relevant for the prediction of higher frequency ground motions. Zhang et al. (Chin J Geophys 56:1412–1417, 2013) and Wang et al. (Chin J Geophys 56:1408–1411, 2013) published their source inversions for the fault rupturing process soon after the April 20, 2013 Lushan earthquake in Sichuan, China. In this study, first, we synthesize two forward source slip models: the value of maximum slip, fault dimension, size, and dimension of major asperities, and corner wave number obtained from Wang's model is adopted to constrain the generation of k^{-2} model and crack model. Next, both inverted and synthetic slip models are employed to simulate the ground motions for the Lushan earthquake based on the stochastic finite-fault method. In addition, for a comparison purpose, a stochastic slip model and another k^{-2} model (k^{-2} model II) with 2 times value of corner wave number of the original k^{-2} model (k^{-2} model I) are also employed for simulation for Lushan event. The simulated results characterized by Modified Mercalli Intensity (MMI) show that the source slip models based on the inverted and synthetic slip distributions could capture many basic features associated with the ground motion patterns. Moreover, the simulated MMI distributions reflect the rupture directivity effect and the influence of the shallow velocity structure well. On the other hand, the simulated MMI by

stochastic slip model and k^{-2} model II is apparently higher than observed intensity. By contrast, our simulation results show that the higher frequency ground motion is sensitive to the degree of slip roughness; therefore, we suggest that, for realistic ground-motion simulations due to future earthquake, it is imperative to properly estimate the slip roughness distribution.

Keywords Stochastic finite-fault model · Strong ground motion · 2013 Lushan $M_w6.6$ earthquake · Corner wave number · k^{-2} model · Crack model

1 Introduction

According to China Earthquake Networks Center, on April 20, 2013, an earthquake of $M_S7.0$ struck Lushan, Sichuan province, China. This event is another violent thrust earthquake following 2008 Wenchuan $M_S8.0$ event which also occurred on the Longmenshan fault zone. The U.S. Geological Survey (USGS) assigned a magnitude of $M_w6.6$ with the epicentral location of 30.308°N, 102.888°E, and focal depth of 14.0 km for this event (USGS 2013). As of April 26, 2013, Lushan earthquake affected more than 200 million people, 196 people were killed, 21 people were missing, 13,484 people were injured, and more than 186,300 housing collapsed. Figure 1 shows the epicentral location (blue star), the topographic map and $M_S \geq 3.0$ aftershocks (red circles) of Lushan earthquake. According to Xu et al. (2013), Lushan earthquake occurred on the southern segment of the Longmenshan thrust belt between the Bayan Har and south China blocks. The relocated aftershocks, focal mechanism solutions, and surface structural geology further demonstrated that the seismogenic fault of Lushan event is a blind reverse fault.

As we know, estimation of slip distribution on fault plane is one of the most fundamental issues for source inversion

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Fig. 1 Locations of main shock (blue star) and $M_S \geq 3.0$ aftershocks (red circles) of the 2013 Lushan $M_W 6.6$ earthquake, where aftershocks are from April 20, 2013 to October 1, 2013

relating to fault rupture process. Zhang et al. (2013) and Wang et al. (2013) published their source inversions for rupture process soon after Lushan event, and slip models from longer period ground motions are then inverted, respectively. In strong ground-motion studies, if the slip distribution associated with rupture, radiation patterns, and medium parameters relating to the seismic wave propagation or path effect are well known, the ground motion can be predicted numerically. From another aspect, a large amount of works have also suggested that variable source slip models inverted from longer period ground-motion recording are relevant for the prediction of higher frequency ground motions (Hartzell et al. 1996; Kamae and Irikura 1998). Note that, characteristics of fault slip distribution actually play an important role to affect the high-frequency seismic radiation (Causse et al. 2010), and the roughness degree of the slip distribution thus becomes crucial for the strong ground-motion predication. In this study, our main objective is to investigate the validity of source slip models by strong ground-motions simulation. The simulated peak ground accelerations (PGA) and velocities (PGV) are converted into regional MMI distributions through empirical relationship, and synthetic MMI maps are compared to field observations. Another objective in this paper is to discuss the effects of slip heterogeneity on strong ground motions.

2 Slip models

2.1 Inverted fault slip models

2.1.1 Wang's model

According to the fast inversion by Wang et al. (2013), they assigned a magnitude of $M_W 6.7$ with strike and dip of 205° , 38.5° for Lushan earthquake. In Wang's slip model, the fault

rupture plane is discretized into 11 subfaults along-strike direction and 7 subfaults along down-dip direction, and the total length and width of the rupture fault are 66 km and 35 km, respectively. The focal mechanism solution also indicated that this event exhibits a pure thrust faulting, and the maximum slip displacement is about 1.6 m. It is clear that this slip model is composed by two major asperities: the first one located near the upper left of the hypocenter, and the second one located in the lower right of the hypocenter. In order to facilitate the comparison among inverted slip models, we interpolated them onto $1 \text{ km} \times 1 \text{ km}$ grid spacing such that the power spectral decays are directly comparable. A map view of this slip model and its Fourier amplitude is shown in Fig. 2. The interpolated models are padded with zero-slip subfaults to achieve 128 subfaults along each direction for wave number spectra calculation.

2.1.2 Zhang's model

Based on the teleseismic body waveform data, Zhang et al. (2013) also inverted the rupture process of Lushan event. The moment magnitude they assigned is $M_W 6.8$ with strike and dip of 219° , 33° , respectively. The fault rupture plane is about 63-km long and 48-km down dip in width, respectively, and the maximum slip displacement is about 1.30 m. In this slip model, the fault is discretized into 21 subfault elements along-strike and 16 elements along down-dip direction. A map view of this slip model and its Fourier amplitude are also shown in Fig. 2.

2.2 Synthetic slip models

The k^{-2} model and crack model are two well-known kinematic source models to describe slip distributions on the ruptured fault surface. In this study, in addition to two inverted slip models (Zhang's model and Wang's model), we also introduce two synthetic source slip models which are constrained by Wang's model. We will illuminate the constraints in detail in the following.

2.2.1 Crack model with a constant-stress drop

Compared with the dislocation model, stress drop of crack model on the fault is specified, rather than the amount of slip (Segall 2010). Under the constant-stress drop crack model, the slip on a crack could be expressed as

$$s(z) = S \sqrt{1 - \left(\frac{z}{a}\right)^2}, \quad |z| < a, \quad (1)$$

where a is the radius of the crack, S is the maximum slip, z represents the distance to the center of the crack (Segall 2010). Note that, two asperities of Wang's model are roughly circular which could be simulated by crack model.

Fig. 2 Inverted slip models for Lushan earthquake and wavenumber spectrum maps of inverted slip models. **a** Wang's model inverted by Wang et al. (2013); **b** Wavenumber spectrum maps of Wang's model; **c** Zhang's model inverted by Zhang et al. (2013); **d** Wavenumber spectrum maps of Zhang's model. The *star* indicates the hypocenter location

Graves and Pitarka (2010) divided the kinematic rupture slip model into two parts: a low-wavenumber deterministic part which represents the gross feature of slip distribution and a high-wavenumber stochastic part. In wavenumber domain, the final slip Fourier spectrum amplitude $U(k_x, k_y) = D(k_x, k_y)F + S(k_x, k_y)(1 - F)$, where k_x and k_y are the horizontal and vertical wavenumbers. $D(k_x, k_y)$ is the 2D Fourier transform of slip model derived by waveform inversion. $D(k_x, k_y)F$ represents the gross feature of slip distribution. F is a wavenumber filter given by

$$F = \left[1 + \left(c_s^2 k_x^2 + c_d^2 k_y^2 \right)^N \right]^{-1} \quad (2)$$

where c_s^{-1} and c_d^{-1} specify the transition between the deterministic and stochastic parts of the spectrum, and N is governing the sharpness of the transition. The stochastic part $S(k_x, k_y)$ is given by

$$S(k_x, k_y) = \frac{D_0}{\sqrt{a_s a_d}} A(k_x, k_y) e^{i\theta}, \quad (3)$$

$D_0 = D(0, 0)$. a_s and a_d are along-strike and down-dip correlation lengths, respectively. Following Mai and Beroza (2002),

$$\begin{cases} \lg(a_s) \approx -2.5 + 0.5M_W \\ \lg(a_d) \approx -1.5 + 0.33M_W. \end{cases} \quad (4)$$

$\lg$ is the base 10 logarithm of a number. The factor $D_0/\sqrt{a_s a_d}$ ensures that the stochastic portion of the amplitude spectrum is properly scaled to the desired mean slip value. $A(k_x, k_y)$ is the von Karman correlation function given by Mai and Beroza (2002):

$$A(k_x, k_y) = \left[\frac{a_s a_d}{(1 + K^2)^{H+1}} \right]^{1/2}, \quad (5)$$

where $K^2 = a_s^2 k_x^2 + a_d^2 k_y^2$ is the normalized wavenumber, H is the Hurst exponent. θ is a random number uniformly distributed between $-\pi$ and π . In this study, with Eq. (1), the deterministic part (the gross feature) is composed by

Fig. 3 Synthetic slip models for Lushan earthquake. **a** Crack model constrained by Wang's model; **b** k^{-2} model I constrained by Wang's model; **c** k^{-2} model II. The *star* indicates the hypocenter location

two asperities that have the same size, location, and maximum slip as Wang's model. As to the stochastic part, the value of D_0 is adopted from Wang's model; in this way, the stochastic part will have the similar property with Wang's model. Following Graves and Pitarka (2010), we set $H = 0.75$, $N = 4$, $c_s = dL$, and $c_d = dW$, where dL and dW are the subfault length and width from the original slip-inversion model, respectively. We transform the stochastic part back into spatial domain and take the maximum value between deterministic part and stochastic part as the final slip distribution (Fig. 3a).

2.2.2 k^{-2} model

Just like the analysis of displacement amplitude, in many studies, the slip distribution complexity is described by amplitude Fourier spectrum. Herrero and Bernard (1994) proposed a kinematic self-similar random slip distribution with k^{-2} decay of amplitudes at high wave numbers. They showed that such slip distributions, together with a constant rupture velocity and a specific k -dependent risetime, lead to the ω^{-2} spectral falloff. The k^{-2} rupture model has already been successfully used in the strong ground-motion simulation both for past as well as future earthquakes. For a rectangular fault plane with length L and width W , Gallovic and Brokesova (2004) used the spatial 2D Fourier spectrum of the slip distribution in the following form:

$$D(k_x, k_y) = \frac{\bar{D}LW}{\sqrt{1 + \left[\left(\frac{k_x}{k_{cx}}\right)^2 + \left(\frac{k_y}{k_{cy}}\right)^2\right]}} \exp(i\Phi(k_x, k_y)), \quad (6)$$

where $\bar{D}$ denotes the mean slip, $\Phi(k_x, k_y)$ is the phase spectrum, and k_x and k_y are the horizontal and vertical wavenumbers, respectively. The terms k_{cx} and k_{cy} are corner wave numbers in along-strike and down-dip directions. k_{cx} and k_{cy} are defined as K/L_c and K/W_c , respectively, where K is a dimensionless constant, and L_c and W_c are characteristic fault length and width, respectively. For the assumed kinematic k^{-2} source model, the value of parameter K is often taken as 1, and the characteristic fault length and width L_c , W_c are taken as fault plane with length L and width W , respectively (Gallovic and Brokesova 2004). According to Herrero and Bernard (1994), $\Phi(k_x, k_y)$ is considered random at any wave number except the circle $k^2 \leq (1/L)^2 + (1/W)^2$ for which the phase is chosen, so that the final slip is concentrated in the center of the rectangular fault. In this study, the fault dimensions, mean slip, and corner wave numbers are cited from Wang's model to generate the k^{-2} model called " k^{-2} model I" (Fig. 3b). For contrast, we generate another k^{-2} model with 2 times the corner wave number value of k^{-2} model I and we called this model as " k^{-2} model II" (Fig. 3c).

2.3 Calculation of corner wave number

In this paper, we take $k_c = \sqrt{k_{cx}^2 + k_{cy}^2}$ as the indicator of corner wave number level for each slip model. The corner wave number k_c can be seen as a measure for the roughness degree of the slip distribution. For a given characteristic fault length, small values of k_c result in one large, smooth asperity. For larger value of k_c , the gradient of slip distribution increases, and the slip model becomes rougher and contains more small-scale slip heterogeneities. The corner wave number is calculated from raw slip distributions (Fig. 4). According to Causse et al. (2010), the amplitude spectra of each slip image are calculated by 2-D Fourier transformation, and then the slip spectra are normalized and compared to a theoretical 1-D k^{-2} model defined as

$$D_{\text{mod}}(k) = \frac{1}{\sqrt{1 + \left(\frac{k}{k_c}\right)^4}}, \quad (7)$$

where k is the wavenumbers, k_c is the corner wavenumber. The parameters k_{cx} and k_{cy} are assessed by minimizing the misfit E expressed as

$$E = \sum_{k \in [0, k_N]} [\lg(D_{\text{obs}}(k)) - \lg(D_{\text{mod}}(k))]^2, \quad (8)$$

where D_{obs} is the observed slip spectrum, k_N is the Nyquist wave number.

In the generation of k^{-2} model I, the values of k_{cx} and k_{cy} are just cited from Wang's model; however, due to the computational errors from Fast Fourier transform and its inverse transform, there is deviation of corner wave number value between k^{-2} model I and Wang's model in strike and down-dip direction. Table 1 summarizes corner wave number values for all five slip models. Obviously, k^{-2} model II has the highest corner wave number, and the value of Zhang's model is slightly higher than the other three models. A same characteristic of the calculation for four slip models is that k_{cx} is lower than along dip k_{cy} . This corresponds to the expectation of Causse et al. (2010) because the number of along down-dip subfaults is generally lower. Causse et al. (2010) suggested that slip distribution with large corner wave number is likely to produce higher peak ground accelerations (PGA). Thus, we could expect that the simulated ground-motion level of k^{-2} model II might higher than

others. A comparison between ground-motion levels through Lushan region is useful in our understanding of the sensitivity of near-ground strong motions to the heterogeneous slip distribution.

3 Simulation method (Algorithm)

3.1 Model parameters of Lushan event

In this work, we use the common and well-known simulation methods: the stochastic finite-fault simulation code (EXSIM, Motazedian and Atkinson 2005; Boore 2009). The stochastic finite-fault model is an extension of the point-source stochastic method (Boore 1983, 2003) which includes the rupture propagation along an extended fault (Ameri et al. 2011). In EXSIM, the fault is divided into N subfaults; each of them is considered as a point source, emitting an ω -square spectrum. Ground motions produced by subfaults are summed in the time domain with a proper time delay, to obtain the ground motions from the entire fault. EXSIM has several significant advantages over previous stochastic finite-fault models, including independence of results from subfaults size, conservation of radiated energy, and the ability to have only a portion of the fault active at anytime during the rupture (simulating self-healing behavior (Heaton 1990)). It has been widely used in strong ground-motions predication and simulation (Atkinson and Boore 2006; Shen et al. 2013).

In stochastic algorithm, earthquake stress drop is the most important input parameter controlling ground-motion levels at intermediate-to-high frequency. We consider two methods to calculate the value of stress drop. First, according to Brune (1970, 1971), assuming a complete stress release, in the context of a kinematic source model, the estimation for the stress drop is given by

$$\Delta\sigma = \frac{7M_0}{16a^3}, \quad (9)$$

where a is the radius of the circular crack, and M_0 is the moment. The stress drop value then is calculated as about 5.06 MPa from Wang's model. Second, for a given slip distribution D on a planar fault, Andrews (1978, 1980) developed a formulation which relates stress change to slip distribution in wave number domain:

Table 1 Summary of the corner wave number value for all five slip models as shown in Figs. 2 and 3

	Wang's model	Zhang's model	crack model	k^{-2} model I	k^{-2} model II
k_{cx} (10^{-4}m^{-1})	0.59	0.982	1.17	0.78	1.52
k_{cy} (10^{-4}m^{-1})	1.49	1.44	1.30	1.40	2.70
k_c (10^{-4}m^{-1})	1.60	1.74	1.75	1.60	3.1

Fig. 4 Calculation of corner wave numbers for slip models as shown in Figs. 2 and 3. The solid line indicates the theoretical 1D k^{-2} model; the circles indicate the slip spectrum, and the dashed lines denote values of k_{cx} and k_{cy}

$$\Delta\sigma(k) = K(k)D(k), \quad (10)$$

where $K(k)$ is the static stiffness matrix, and $D(k)$ is the two-dimensional Fourier transform of slip D (Ripperger and Mai 2004). Calculation of static stress changes for a given slip distribution on the fault, therefore, only requires the Fourier transformation of actual slip distribution into the wave number domain by using Eq. (10) and with an inverse transformation of $\Delta\sigma(k)$ back into space domain. Hanks (1979) expected the stress drop to be realized across an area of incipient rupture A from the root-mean-square (rms) value of stress change:

$$\langle\Delta\sigma\rangle^2 = \frac{1}{A} \iint_A \Delta\sigma(x, y)^2 dx dy, \quad (11)$$

where $\Delta\sigma(x, y)$ is the stress change of subfault. Written in discrete form

$$\langle\Delta\sigma\rangle^2 = \frac{1}{N} \sum [\Delta\sigma(i, j)]^2. \quad (12)$$

N is the number of subfaults. Following this method, the value of stress drop based on Wang's model is 4.22 MPa. In the practical calculation, stress drop is set as 4.5 MPa. The frequency-dependent attenuation relation $Q = 400f^{0.434}$ developed for this region by Jin and Aki (1988) and Mitchell et al. (1997) is taken into account. The kappa value is taken as 0.058 from the empirical relationship between kappa parameter and the magnitude given by Atkinson (1996). The study area is known as one of the nine SCRs (stable continental regions) with no orogenic activity after the early Cretaceous (Johnston 1996a). For SCRs, they are similar in average crustal thickness, anelastic attenuation (Jin and Aki 1988; Mitchell 1995), and crustal deformation rates (Johnston 1994b). As there is no specific geometrical model developed for the study area,

Table 2 Parameters used in simulations for 2013 Lushan M_W 6.6 earthquake

Parameter	Value	Parameter source
Latitude, longitude	30.308°N, 102.888°E	USGS (2013)
Focal mechanism	Strike: 205° Dip: 38.5°	Wang et al. (2013)
Moment magnitude	6.6	USGS (2013)
Depth of top of rupture	2.0 km	Wang et al. (2013)
Stress drop	4.5 MPa	
Fault dimension	66 km × 35 km 63 km × 48 km	Wang et al. (2013) Zhang et al. (2013)
No. of fault along strike, dip	16, 8	
Rupture velocity	0.8 β	Atkinson and Boore (2006)
Pulsing percentage	50 %	Motazedian and Atkinson (2005)
Shear-wave velocity	3.7 km/s	
Quality factor	400 $f^{0.434}$	Mitchell et al. (1997)
Kappa	0.058	Atkinson (1996)
Density	2.8 g/cm ³	
Geometric spreading	1/ R , $R < 70$ km 1.70 km $\leq R < 130$ km $R^{-0.5}$, $R \leq 130$ km	Eastern North American (Atkinson and Boore 1995)
Duration properties	$r_{\min} = 10$ km $r_{d1} = 70$ km $r_{d2} = 130$ km $Dur_{\min} = 0$ s $b_1 = 0.16$ $b_2 = -0.03$ $b_3 = 0.04$	Eastern North American (Atkinson and Boore 1995)

the geometrical model developed for Eastern North America (Atkinson and Boore 1995) is used in present study. Table 2 summarizes the main characteristics in terms of source and path parameters.

3.2 Site effect correction

As a result of the combined effects of velocity gradient in the crust and the weathered layer of rock in the top few meters, amplification occurs for the rock site. Thus, site correction is significant for strong ground-motions simulation. Atkinson and Boore (2006) used the horizontal-to-vertical component ratios (H/V ratios) to estimate the amplification, and the expected amplification was

Fig. 5 Site-condition map inverted from topographic slope for the study area

calculated from the regional shear-wave velocity profile. However, for regions that lack these velocity profiles, this method is unsuitable. In this study, we prefer the method proposed by Boore and Atkinson (2007), which is more applicable as they derived an empirical relationship. The site correction of the resultant PGA and PGV is approximated using the following equations:

$$\begin{cases} \ln(\text{PGA}') = \ln(\text{PGA}) - 0.36 \ln(V_S^{30}/760) \\ \ln(\text{PGV}') = \ln(\text{PGV}) - 0.6 \ln(V_S^{30}/760) \end{cases}, \quad (13)$$

where $\ln$ represents natural logarithm of a number, and V_S^{30} , the average shear-velocity down to 30 m, in each site, is obtained from the USGS's global V_S^{30} dataset inverted by Wald and Allen (2007), based on the tomography and surface geology. In Eq. (13), PGA and PGV are the original data from the simulation by EXSIM without site correcting, and PGA' and PGV' are the corrected results corresponding to the local V_S^{30} . The applicability of this empirical method to ground-motion predictions has been tested and verified by numerous researchers and in various seismotectonic environments (Wald et al. 2006, Wald and Allen 2007). Figure 5 shows the V_S^{30} distribution for the study area. Compared with Fig. 1, it is clear that V_S^{30} values in western mountains are significantly higher than that of the eastern plains (Chengdu Plain). Note that the Chinese Seismic Intensity Scale is similar to MMI (Hao and Xie 2006); thus, the corrected PGA and PGV are then converted to MMI based on the empirical relation (Atkinson and Kaka 2007) and compared with the observed intensity directly. Moreover, the simulated PGA also is compared with NGA (Next Generation Attenuation Relation, Boore and Atkinson 2007) and station recordings.

Fig. 6 Comparison of the simulated MMI from **a** Wang's model, **b** Zhang's model, **c** Crack model, **d** k^{-2} model I, **e** Stochastic slip model, **f** k^{-2} model II with **g** the observed intensity. The *star* indicates the location of epicenter

4 Simulation results

Based on the EXSIM code, we use both inverted and synthetic slip models to simulate the strong ground motions for Lushan earthquake. In addition, a stochastic slip model introduced by Andrews (1980) is also employed. In the stochastic model, the white noise is generated with Gauss random variable which means the seismic moment will be randomly assigned on subfaults. The simulation is done on a rectangular grid of sites (29°N–31°N, 101.5°E–104.5°E), with a 0.01° spacing. For each site, the code runs for 10 times, and we take the average value of these simulations as the final value of PGA and PGV.

4.1 Comparison with the observed intensity

Figure 6 displays the simulated ground motions characterized by MMI from six-slip models. For both inverted and synthetic slip models, we find that the simulated ground motions (Fig. 6a–d) are able to match several salient features of the ground shaking distributions, such that the correlation between synthetic meizoseismal areas is consistent with the field observation, and the distribution range that other MMI value corresponds is also approximately matched. However, symmetric pattern could be seen in all simulated result along the fault, while the pattern is non-symmetric in the observed map. Possible explanations includes (1) amplification effects are systematically different along the fault, or (2) the dip of the fault is not unique, and this had been confirmed by Xu et al. (2013). The most significant difference between the simulated

MMI and the observed intensity is that the contour shape of the simulation result is not oval shaped. For instance, in Chengdu Plain, intensities increased significantly. That is because we have added the influence of regional V_S^{30} into simulations which reflects the influence of the local terrain. Also, it could be seen from Fig. 6a–d that intensity contours were more elongated toward south supporting the southern directivity effect that is consistent with the observation depicted by field MMI pattern. On the other hand, we also find that the simulated result from stochastic slip model (Fig. 6e) and k^{-2} model II (Fig. 6f) is less appropriate than other slip models (Fig. 6a–d). Especially the area corresponding to IX is significantly larger than observation.

4.2 Comparison with the NGA model and station recordings

The ground-motion variability in empirical equations is quantified by the standard deviation of the logarithm residuals $\sigma_{\lg(\text{PGA})}$ or $\sigma_{\ln(\text{PGA})}$, commonly referred to as “sigma.” It is usually divided into between-event variability and within-event variability (Cotton et al. 2013). The between-event variability can be interpreted as the combined ground-motion variability resulting from event-specific factors (e.g., randomness in the source process) that have not been included in the predictive model. Here, we calculated the between-event variability $\sigma_{\lg(\text{PGA})}$ for all 201×301 points from four slip models. The results range from 0.0037 to 0.2857, and the average value is 0.076; this value is much lower than 0.15–0.20 which is suggested by Morikawa et al. (2008). That is because in our numerical simulations, the only variability is from the slip distribution, while the variability of Morikawa et al. (2008) is from observed data, including rupture direction, focal mechanism, and other physical processes governing seismic

Table 3 Comparison of the observed and simulated acceleration data at ten stations

No.	Station name	Epicentral distance (km)	Horizontal peak ground acceleration	
			Observed (cm s^{-2})	Simulated (cm s^{-2}) (Wang's model/Zhang's model/ crack model/ k^{-2} model I)
1	Baoxing Diban	19.43	1,005.35	506.69/601.07/537.55/513.51
2	Mingshan Keji	27.7	400.71	364.18/382.65/374.57/341.77
3	Qionglai Youzha	28.2	315.49	230.52/300.68/274.90/219.51
4	Lushan Feixian	32.6	387.41	331.47/359.78/366.64/319.95
5	Pujiang Daxing	40.8	184.32	150.66/249.02/197.32/154.06
6	Yingjing Shilong	50.4	253.56	221.66/257.82/266.87/229.89
7	Hanyuan Yidong	89.9	183.43	154.50/195.63/169.54/173.93
8	Dujiang Ziping	98.3	79.16	68.88/109.25/102.57/70.46
9	Kangding Zhuanye	103.7	70.61	82.21/67.56/79.28/85.32
10	Chengdu Zhonghe	108.8	67.08	61.80/73.28/74.14/62.73

radiation and wave propagation. The within-event variability, on the other hand, represents the combined ground-motion variability coming from path- and site-specific factors (e.g., randomness in the site amplification for a given site class). The within-event variability $\sigma_{lg(PGA)}$ for Zhang's model, Wang's model, crack model, and k^{-2} model I are 0.2482, 0.2426, 0.2312, and 0.2508, respectively. These values are reasonable compared with many classical relations that result around 0.15–0.35 (Ambraseys et al. 1996; Abrahamson and Sliva 1997).

The decaying of simulated PGA with distance shows a systematic consistent with NGA (Next Generation Attenuation) given by Boore and Atkinson (2007) (Fig. 7). In the region with distance greater than 100 km, the simulation results could match well with station recordings. However,

as a result of lacking of precisely geometric attenuation model in Sichuan area, we use the attenuation model of North America where is also the stable continental region, and we note that in the range of 0–100 km, several simulation results are less than the recording data, while this region corresponds to the region that the geometric decay is set as $1/R$ and 1 from North America. The differences indicate that geometric spreading model for Sichuan area in 0–100 km may slower than North America from which we adopted.

We select ten stations within 100 km from the epicenter, and the simulated horizontal PGA values from four slip models are compared with the station recordings (Table 3). All the observed data are from China Earthquake Data Center (<http://www.smsd-iem.net.cn/>). Due to the current

Fig. 7 Comparison of the simulated PGA from **a** Wang's model, **b** Zhang's model, **c** Crack model, and **d** k^{-2} model I with NGA and station recordings. The dots indicate the simulated PGA, and triangles indicate station recordings. The solid line denotes NGA (acceleration), and the dashed lines denote 95 % confidential level. Abscissa represents the closest distance to the fault plane R_{rup}

Fig. 8 Decay of mean simulated PGA from **a** Wang's model (red line), **b** Zhang's model (blue line), **c** Crack model (green line), and **d** k^{-2} model I (black line) with R_{rup} (the closest distance to the fault plane). Symbols indicate mean and standard deviation

published latitudes and longitudes of stations only accurate to one decimal place, this might affect our simulation accuracy. As showed in Table 3, most of the simulated data are consistent with the observed data, while the simulated data are generally lower than recorded data in 0–30 km. The biggest difference is found at the first station Baoxing Diban, and the recorded value $1,005.35 \text{ cm s}^{-2}$ is also the maximum instrumental PGA record in China so far. In

addition to the above-mentioned geometric model, alternatively, site amplification effects may be systematically higher than we corrected, and this might also cause of difference between station record and our simulation.

5 Discussion and conclusions

Figure 8 shows the binned decay of mean simulated PGA from four slip models. The attenuation trend is consistent for four models but the larger mean PGA from Zhang's model is clear. This may be due to the higher corner wave number of Zhang's model as that large corner wave number is likely to produce higher PGA. Since the other three models have alike corner wave number value, the differentiation of their mean PGA level is small. Based on k^{-2} model I and k^{-2} model II, we simulate the acceleration time series for station 1, 2, 6, and 9 in Table 3 (Fig. 9). The epicentral distances are 19.43, 27.7, 50.4, and 103.7 km, respectively. Accelerograms in Fig. 9 show that k^{-2} model I resulted in relative low-amplitude ground motions, on the contrary, k^{-2} model II with more heterogeneous static slip leads to large, high-frequency amplitude.

We have mentioned that in the generation of k^{-2} model I and k^{-2} model II, they have the same parameter (including

Fig. 9 Simulated acceleration time series from k^{-2} model I and k^{-2} model II. Each row of plots is for a station with name on the top, and the number represents the serial number of stations in Table 3. Epicentral distances of the stations 1, 2, 6, and 9, are 19.43, 27.7, 50.4, and 103.7 km, respectively

the fault dimension, mean slip value, and so on) except the value of corner wave number which can be seen as the slip roughness parameter. The corner wave number value of k^{-2} model II is two times of k^{-2} model I (Fig. 3), so k^{-2} model I results in more smooth slip distribution. It is clear that, from Fig. 6, the simulated MMI level from k^{-2} model II is higher than k^{-2} model I, moreover, an important feature is that the meizoseismal area ($\text{MMI} \geq \text{IX}$) is larger than k^{-2} model II. Because the ground motions at near-fault distances is affected by amplitudes at intermediate-high frequencies, combining the result in Fig. 9, we believe that the high-frequency ground is strongly sensitive to the degree of slip roughness, and is thus of major interest for earthquake engineering. Causse et al. (2009) showed that slip roughness is directly related with the localized stress drop which is the fundamental parameter in stochastic finite-fault source model of Motazedian and Atkinson (2005) and is correlated with PGA and PGV. Therefore, for realistic ground-motion simulations due to future earthquake, it is imperative to properly estimate the slip roughness distribution. Somerville et al. (1999) assessed the roughness variability and established the empirical relationship for systematic features of the scaling of slip models with magnitude. However, their result was obtained from a rather small set of events, which restricted the reliability. Causse et al. (2010) updated the model of Somerville et al. (1999), and analyzed a larger database of finite-source rupture models. With the improvement of techniques and methods, the inverted fault slip model number is increasing, but the number of available slip models is still rather small due to the uncertainty of the inversion. On the other hand, present empirical relationships only relate the magnitude to express slip roughness. However, kinematic characteristics inside the epicentral region cannot be modeled by magnitude alone (Adrian and Nelson 2002), and the use of multiple parameters could reduce the roughness variability for a single source (Causse et al. 2010).

In this paper, first we generate synthetic slip models base on the inverted source slip model. Then the calculation of corner wave number is applied for these slip models. Next, these slip models are used to simulate the ground motions for Lushan earthquake base on the stochastic finite-fault method. The simulation characterized by MMI show that the result base on inverted and synthetic slip distributions could capture most basic features of ground motions. Moreover, the simulated MMI distributions reflect obvious rupture directivity effect and the influence of the shallow velocity structure well. While the result of stochastic slip model and k^{-2} model II is apparently higher than observed intensity. The decaying of simulated PGA with distance shows a systematic consistent with NGA, and by comparing the simulated PGA with the station recordings, we find that the geometric spreading

model for Sichuan area may be slower than North America. Therefore, it is desirable to estimate the median ground-motion levels and their variability for a suit of simulations with precise regional crustal model including geometrical spreading model and Q-model. The comparison between intensity distribution and accelerograms from k^{-2} model I and k^{-2} model II shows that the higher frequency ground is strongly sensitive to the degree of slip roughness; therefore, we suggest that, for realistic ground-motion simulations due to future earthquakes, it is imperative to properly estimate the slip roughness distribution.

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References

- Abrahamson NA, Sliva WJ (1997) Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismol Res Lett* 68:94–127
- Adrian MC, Nelson TK (2002) Intensity attenuation relationship for the South China region and comparison with the component attenuation model. *J Asian Earth Sci* 20:775–790
- Ambraseys NK, Simpson KA, Bommer JJ (1996) Predication of horizontal response spectra in Europe. *Earthquake Eng Struct Dym* 25:371–400
- Ameri G, Emolo A, Pacor F, Galovic F (2011) Ground motion simulation for the 1980 *M*6.9 Irpinia earthquake (Southern Italy) and scenario events. *Bull Seismol Soc Am* 101(3):1136–1151
- Andrews DJ (1978) Coupling of energy between tectonic processes and earthquakes. *J Geophys Res* 83:2259–2264
- Andrews DJ (1980) A stochastic fault model: 1 static case. *J Geophys Res* 85:3867–3877
- Atkinson GM (1996) The high-frequency shape of the source spectrum for earthquakes in eastern and western Canada. *Bull Seismol Soc Am* 86:106–112
- Atkinson GM, Boore DM (1995) Ground-motion relations for eastern North America. *Bull Seismol Soc Am* 85:17–30
- Atkinson GM, Boore DM (2006) Earthquake ground-motion prediction equations for eastern North America. *Bull Seismol Soc Am* 96:2181–2205
- Atkinson GM, Kaka SI (2007) Relationships between felt intensity and instrumental ground motion in the central United States and California. *Bull Seismol Soc Am* 97(2):497–510
- Boore DM (1983) Stochastic simulation of high-frequency ground motion based on seismological models of the radiated spectra. *Bull Seismol Soc Am* 73:1865–1894
- Boore DM (2003) Simulation of ground motion using the stochastic method. *Pure appl Geophys* 160:635–676
- Boore DM (2009) Comparing stochastic point-source and finite-source ground-motion simulations: SMSIM and EXSIM. *Bull Seismol Soc Am* 99:3202–3216
- Boore DM, Atkinson GM (2007). Boore-Atkinson NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters. PEER Report. Pacific Earthquake Engineering Research Center
- Brune JN (1970) Tectonic stress and spectra of seismic shear waves from earthquakes. *J Geophys Res* 75(26):4997–5009
- Brune JN (1971) Correction to tectonic stress and spectra of seismic shear waves from earthquakes. *J Geophys Res* 76(20):5002

- Causse M, Chaljub E, Cotton F, Cecile Cornou (2009) New approach for coupling $k = 2$ and empirical Green's functions: application to the blind prediction of broad-band ground motion in the Grenoble basin. *Geophys J Int* 179:1627–1644
- Causse M, Cotton F, Mai PM (2010) Constraining the roughness degree of slip heterogeneity. *J Geophys Res* 115:B05304. doi:10.1029/2009JB006747
- Cotton F, Archuleta R, Causse M (2013) What is sigma of the stress drop? *Seismol Res Lett* 84(1):42–48
- Gallovic F, Brokesova J (2004) On strong ground motion synthesis with the k^{-2} slip distribution. *J Seismol* 8:211–224
- Graves RW, Pitarka A (2010) Broadband ground-motion simulation using a hybrid approach. *Bull Seismol Soc Am* 100:2095–2123
- Hanks T (1979) b values and $\omega^{-\gamma}$ seismic source models: Implications for tectonic stress variations along active crustal fault zones and the estimation of high-frequency strong ground motion. *J Geophys Res* 84(B5):2235–2242
- Hao M, Xie LL (2006) Research and suggestion of extent value of physical measure in seismic intensity scale of China. *J Harbin Inst Technol* 38:1041–1044
- Hartzell SH, Liu P, Mendoza C (1996) The 1994 Northridge, California earthquake: investigation of rupture velocity, rise time, and high-frequency radiation. *J Geophys Res* 101:20091–20108
- Heaton TH (1990) Evidence for and implications of self healing pulses of slip in earthquake rupture. *Phys Earth Planet Inter* 64:1–20
- Herrero A, Bernard P (1994) A kinematic self-similar rupture process for earthquakes. *Bull Seismol Soc Am* 84:1216–1228
- Jin A, Aki K (1988) Spatial and temporal correlation between coda Q and seismicity in China. *Bull Seismol Soc Am* 78:741–769
- Johnston AC (1994b). Seismotectonic interpretations and conclusions from the stable continental region seismicity database. In: Schneider JF (ed) The earthquakes of stable continental regions: assessment of large earthquake potential, Chapter 4, pp. 4-14-103, EPRI Rpt. TR-102261, Electric Power Res. Inst., Palo Alto
- Johnston AC (1996) Seismic moment assessment of earthquakes in stable continental regions—I. Instrumental seismicity. *Geophys J Int* 125:381–414
- Kamae K, Irikura H (1998) Source model of the 1995 Hyogoken Nanbu earthquake and simulation of near-source ground motion. *Bull Seismol Soc Am* 88:400–412
- Mai PM, Beroza GC (2002) A spatial random field model to characterize complexity in earthquake slip. *J Geophys Res* 107, doi:10.1029/2001JB000588
- Mitchell BJ (1995) Anelastic structure and evolution of the continental crust and upper mantle from seismic surface wave attenuation. *Rev Geophys* 33(4):441–462
- Mitchell BJ, Pan Y, Xie JK, Cong LL (1997) Lg coda Q variation across Eurasia and its relation to crustal evolution. *J Geophys Res* 102:22767–22779
- Morikawa N, Kanno T, Narita A, Fujiwara H, Fukushima Y, Guerpinar Y (2008) Strong motion uncertainty determined from observed records by dense network in Japan. *J Seismol* 12:529–546
- Motazedian D, Atkinson GM (2005) Stochastic finite-fault modeling based on a dynamic corner frequency. *Bull Seismol Soc Am* 95:995–1010
- Ripperger J, Mai PM (2004) Fast computation of static stress changes on 2D faults from final slip distributions. *Geophys Res Lett* 31:L18610
- Segall P (2010) Earthquake and Volcano Deformation. Princeton University Press, Princeton
- Shen WH, Zhong Q, Liu BY, Shi BP (2013) Rapid regional estimation of MMI base on the modified stochastic finite fault modeling. *Progress Geophys* 28(2):0695–0705 (in Chinese with English abstract)
- Somerville P, Irikura K, Graves R, Sawada S, Wald D, Abrahamson D, Iwasaki Y, Kawaga T, Smith N, Kowada A (1999) Characterizing crustal earthquake slip models for the prediction of strong ground motion. *Seismol Res Lett* 70(1):59–80
- USGS (2013) <http://comcat.cr.usgs.gov/earthquakes/eventpage/usb000gcdd#summary>. Accessed 30 May 2014
- Wald DJ, Allen TI (2007) Topographic slope as a proxy for seismic site conditions and amplification. *Bull Seismol Soc Am* 97(5):1379–1395
- Wald DJ, Earle PS, Lin KW, Quitoriano V, Worden B (2006) Challenges in rapid ground motion estimation for the prompt assessment of global urban earthquakes. *Bull Earthq Res Inst* 81:273–281
- Wang WM, Hao JL, Yao ZX (2013) Preliminary result for rupture process of April 20, 2013, Lushan earthquake, Sichuan, China. *Chin J Geophys* 56(4):1412–1417 (in Chinese with English abstract)
- Xu XW, Wen XZ, Han ZJ et al (2013) Lushan $M_s7.0$ earthquake: a blind reserve-fault earthquake. *Chin Sci Bull* 58:3437–3443. doi:10.1007/s11434-013-5999-4
- Zhang Y, Xu LS, Chen YT (2013) Rupture process of the Lushan 4.20 earthquake and preliminary analysis on the disaster-causing mechanism. *Chin J Geophys* 56(4):1408–1411 (in Chinese with English abstract)