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Simulation of acceleration field of the Lushan earthquake (Ms7.0, April 20, 2013, China)

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ABSTRACT

The acceleration field of the Lushan earthquake (Ms7.0, April 20, 2013, China) is simulated using a new modified version of the stochastic finite-fault method (EXSIM) based on a dynamic corner frequency approach. To incorporate the effect of heterogeneous slip distribution on the variation of source spectrum, we adopt an empirical source spectral model and derive the corresponding dynamic parameters, which vary with the cumulative seismic moment of the ruptured area.

The new modified method is validated by: 1) comparison of the simulation results with those obtained from the EXSIM method using near-fault ground motion data of the 1994 Northridge earthquake; 2) comparison of simulated PGA contour map inferred from synthetic time histories at 315 grid locations with the observed PGA shakemap for the 2013 Lushan earthquake; 3) comparison of simulated PGA with those predicted by ground-motion prediction equations (GMPEs); and 4) comparison of simulated time histories with observed acceleration records at six strong motion stations during the mainshock of the Lushan earthquake, in which local site response is considered in the simulation. These comparisons confirm the validity of the new simulation procedure for purposes of regional strong ground motion estimation. Limitations of the procedure in modeling the phasing of different arrivals in the seismic signal and near-surface response of geologic deposits are discussed.

1. Introduction

The Lushan earthquake occurred at 08:02 Beijing Time (00:02 UTC) on April 20, 2013. The epicenter was located in Lushan County, Ya'an, Sichuan Province, about 116 km southwest from Chengdu along the Longmenshan fault belt. The magnitude of the earthquake was estimated as M_s 7.0 by the China Earthquake Data Center (CENC) and M_w 6.6 by the United States Geological Survey (USGS). The earthquake resulted in 196 people dead, 21 missing, and at least 11,470 injured (CEA, 2013).

Extensive damage surveys from this and past earthquakes have shown that strong ground motion is the main driving force causing building damages, ground failures associated with liquefaction and landslides, and resulting loss of life. Hence, ground motion time histories are essential for seismic design and nonlinear analysis of key buildings. Regarding countries or regions where there are few strong motion records, such as in most parts of China, it is necessary to simulate ground motion time histories as the input of structural dynamic analysis, according to comprehensive information (Wang and Xie, 2008). However, it is known that only less than 20 seismic stations were set within 200 km from the epicenter of the 2013 Lushan earthquake, and a limited number of recordings were recorded during the mainshock. Therefore, simulating near-fault acceleration time histories and ground motion parameters for the Lushan earthquake could provide the basis for structural dynamic analysis and seismic fortification in post-disaster reconstruction.

Currently, there are three kinds of methods for ground motion simulation, i.e. deterministic method, stochastic method and hybrid method. It is widely recognized that deterministic method could match the ground motions at low frequencies very well whereas stochastic method is the most successful at predicting ground motions at high frequencies. Hybrid method combines the low-frequency advantages of deterministic method with the high-frequency advantages of stochastic method, thereby allowing broadband simulation of time histories (Ameri et al., 2012; Hartzell et al., 1999, 2011; Pitarka et al., 2000, 2002).

Hartzell et al. (1999) compared various ground motion simulation techniques based on their ability to fit the near-fault ground motions of the 1994 Northridge earthquake. They considered 13 combinations of simulation models ranging from the purely stochastic to purely deterministic, including two hybrid approaches. They concluded that the hybrid approach combining the 3D finite-difference, kinematic results at low frequencies with stochastic finite-fault results at high frequencies gave the best fit to the Northridge data. However, according to the interpretation of Motazedian and Atkinson (2005), the purely stochastic model (Beresnev and Atkinson, 1998) performs better than the two

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hybrid methods in predicting both peak acceleration and velocity, but is not as good as the hybrid approach with the 3D finite-difference in predicting the durations.

For the simulation of the Lushan earthquake, we choose stochastic method, instead of deterministic or hybrid method, due to the following reasons: 1) stochastic method has the considerable advantage of being relatively simple and versatile and requiring little details of the earth structure, such as the S-wave velocity and density profiles; 2) it has been successfully used in a variety of studies and tectonic regions (e.g.: Atkinson and Boore, 2006; Atkinson and Silva, 1997, 2000; Beresnev and Atkinson, 1998; Ou and Herrmann, 1990; Ugurhan et al., 2012); 3) even though the accuracy of the hybrid method, including finite difference in a 3D velocity model, is better than that of the stochastic finite-fault method of Beresnev and Atkinson (1998), there is few available and reliable 3D velocity model in Sichuan Province. In addition, most of the borehole data in the study area has a depth less than 25 m, which is not deep enough to build a 3D velocity structure.

The objective of this paper is to simulate the high-frequency portion of strong ground motions for the 2013 Lushan earthquake based mainly on stochastic finite-fault simulation code EXSIM (Motazedian and Atkinson, 2005, MA05 for short), but with some modifications on source spectrum and dynamic corner frequency. We adopt the source spectral model by Masuda (1982) with two empirical parameters by Wang (2001), instead of the Brune (1970) source spectrum with single corner frequency. Accordingly, we use dynamic parameters to replace the function of the dynamic corner frequency.

To verify the validity of the improved method, the 1994 Northridge earthquake is taken as an example to compare the modeling biases of the MA05 and improved method, due to its considerable recordings on rock sites and similar magnitude and mechanism of faulting with the 2013 Lushan earthquake. Then, in order to obtain the acceleration field of the Lushan earthquake, acceleration time histories are simulated at a grid of locations and then used to infer a near-fault PGA contour map. For the purpose of confirming the effectiveness of our simulating procedure and input parameters, this paper compares the simulated PGA acceleration field with the observed PGA contour map by Chen et al. (2013), and the attenuation of simulated PGA with four ground-motion prediction equations (GMPEs) by Lei et al. (2007), Yu and Wang (2006), Abrahamson and Silva (2008) and Boore and Atkinson (2008). Further comparisons are made between the simulated and observed acceleration time histories at rock and soil sites, in terms of peak value, duration and response spectra.

2. Finite-fault method

2.1. Previous method

In finite-fault modeling of earthquake ground motions, the fault plane is discretized into N subfaults with each considered as a small point source (Hartzell, 1978). The rupture spreads radially from the hypocenter at a certain rupture speed and activates each subfault when arriving there. The simulated ground motions from all the subfaults are summed with a proper time delay in the time domain, where each subfault is calculated by the stochastic point-source method (Boore, 1983, 2003), to obtain the acceleration time history $a(t)$ from the entire fault:

$$a(t) = \sum_{i=1}^{N_L} \sum_{j=1}^{N_W} a_{ij}\left(t + \Delta t_{ij}\right), \quad (1)$$

where N_L and N_W are the number of subfaults along the length and width of the fault, respectively, and Δt_{ij} is the time delay for the radiated wave from the hypocenter to the ijth subfault and from the ijth subfault to the observation point (Motazedian and Atkinson, 2005).

Several studies have shown that this model yields ground motion, $a(t)$, for a large fault depends on the subfault size, which controls the amplitude of source spectrum at intermediate frequencies (Joyner and Boore, 1986; Beresnev and Atkinson, 1998, 2002). That is to say, to improve estimates of observed ground motions for a large fault, some constraints on subfault size are necessary. Besides, the stochastic finite-fault method only models shear wave propagation from the fault plane without describing the phasing of various waves in the seismic signal at large distances, such as early body-waves (including P-wave and S-wave) followed by later surface-waves. At near-source distances, stochastic methods have not adequately characterized the coherent long-period pulses which may control the amplitude, duration and response spectra of ground motions at periods longer than about 1 s (Motazedian and Atkinson, 2005).

In order to reduce the influence of subfault size on simulated ground motions, Motazedian and Atkinson (2005) modified the Brune (1970) ω^2 source spectrum for each subfault with the following dynamic corner frequency:

$$A_{ij}(f) = \frac{CM_{0ij}(2\pi f)^2}{1 + \left(f/f_{0ij}\right)^2}, \quad (2)$$

where M_{0ij} and f_{0ij} are the seismic moment and corner frequency of the ijth subfault, respectively. The corner frequency of the ijth subfault is defined as below:

$$f_{0ij}(t) = N_R(t)^{-1/3} 4.9 \times 10^6 \beta(\Delta\sigma/M_{0ave})^{1/3}, \quad (3)$$

where $N_R(t)$ is the cumulative number of ruptured subfaults at time t, $M_{0\text{ave}} = M_0/N$ is the average seismic moment of the subfaults. As the rupture propagates to the edge of the fault, the number of ruptured subfaults increases, which leads to a decrease in the corner frequency of the subfaults (Motazedian and Atkinson, 2005).

Though the dynamic corner frequency mentioned above could almost eliminate the influence of fault-discretization scheme on ground motion simulation and avoid the constraints on subfault size, it has two deficiencies: 1) the corner frequency of subfaults mainly depends on the order of rupture, which does not reflect the effect of slip distribution on the corner frequency and weakens the contribution of asperities on the radiation of high-frequency seismic waves; 2) when the rupture propagates to all the subfaults on the fault plane, the corner frequency of the subfaults reaches its lower limit, i.e. the corner frequency of the entire fault, which is an underestimation of the corner frequency (Sun et al., 2009).

2.2. Improved method

In this study, a variation of the MA05 method is proposed. The corner frequency of the ijth subfault is defined as below:

$$f_{0ij} = 4.9 \times 10^6 \beta\left(\Delta\sigma/M_{0ij}\right)^{1/3}, \quad (4)$$

where M_{0ij} is the seismic moment of the ijth subfault. The seismic moment of the entire fault, M_0, is distributed to all the subfaults, according to the slip value of each subfault:

$$M_{0ij} = \frac{M_0 D_{ij}}{\sum_{k=1}^{nl} \sum_{l=1}^{nw} D_{kl}}, \quad (5)$$

where D_{ij} is the relative slip weight of the ijth subfault. The model of Masuda (1982) is adopted as the source spectrum for each subfault, in which the acceleration spectrum of the ijth subfault is described as below:

$$A_{ij}(f) = \frac{CM_{0ij}(2\pi f)^2}{\left[1 + \left(f/f_{0ij}\right)^a\right]^b}, \quad (6)$$