Lg-Q model and its implication on high-frequency ground motion for earthquakes in the Sichuan and Yunnan region

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Abstract: Low-rise buildings are susceptible to high-frequency ground motion. The high-frequency ground motions at regional distances are mainly controlled by crustal Lg waves whose amplitudes are typically much larger than those of body waves. In this study, we develop a Lg-wave Q model for the Sichuan and Yunnan region in the frequency band of 0.3–2.0 Hz using regional seismic records of 1166 earthquakes recorded at 152 stations. Comparison between the observed pattern of ground motion from real earthquake and model prediction demonstrates the robustness and effectiveness of our Lg-Q model. Then, assuming that the Lg-wave Q structure is the main factor affecting the propagation of the high-frequency ground motions, we calculate the spatial distributions of high-frequency ground motions from scenario earthquakes at different locations in the region using the average Lg-wave attenuation model over the frequency band of 0.3–2.0 Hz. We also use the Lg-Q model to estimate the distribution of cumulative energy of high-frequency ground motions based on the historical seismicity of the Sichuan and Yunnan region. Results show that the Lg-Q model can be used effectively in estimating the spatial distribution of high-frequency seismic energies and thus can contribute to the assessment of seismic hazard to low-rise buildings.

Keywords: Lg-wave attenuation model; high-frequency ground motions; seismic hazards; low-rise buildings

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1. Introduction

The Sichuan and Yunnan region is located in the southeast of the uplifted Tibetan Plateau. Its complex geological structures are closely related to the collision between the Indian and Eurasian plates. This region consists of a number of tectonic blocks including the Songpan–Garzê Block, Qiangtang Block, Sichuan–Yunnan Rhombic Block, Yunnan–Burma Block and Yangtze Block as well as the Sichuan Basin (Figure 1). Dividing these tectonic blocks are major active fault zones in the region such as the Lancangjiang Fault Zone (LCJFZ), the Jinshajiang Fault Zone (JSJFZ), the Red River Fault Zone (RFFZ), the Lijiang–Xiaojinhe Fault Zone (LXFZ), the Xianshuihe–Anninghe–Zemuhe Fault Zone (XAZFZ), the Xiaojiang Fault Zone (XJFZ), and the Longmenshan Fault Zone (LMSFZ) where the great Wenchuan Mw 7.9 earthquake occurred on May 12, 2008 (e.g., Su YJ and Qin JZ, 2001; Xu XW et al., 2003; Han WB and Jiang GF et al., 2004). Strong crustal deformation and fault displacement since the Cenozoic have led to a high level of seismicity in the Sichuan and Yunnan region (e.g., Han WB and Jiang GF et al., 2004; Yi GX et al., 2008). Therefore, studying the ground motions caused by regional earthquakes in this region is of great importance for earthquake disaster prevention and mitigation.

The study of ground motion has employed two main methods. Numerical simulation methods, which use earthquake source models and wave equation solvers to calculate theoretical seismograms (e.g., Boore, 1983; Chen XF, 1999), are widely used in predicting ground motions. Although numerical methods can provide ground motions at any location, they incur high computational costs and are usually not suitable for calculating high-frequency ground motions above 1 Hz. In order to avoid dealing with the complex effects from source, propagation, and site amplification of individual earthquakes, a second method has been developed: empirical statistical relations of ground motion attenuation combine those effects on ground motions in specific regions (e.g., Hartzell, 1978; Kanamori, 1979; Irikura, 1983; Joyner and Boore, 1986; Takemura and Ikeura, 1988; Dan et al., 1990). Attenuation relations overcome difficulties in the calculation of Green’s functions and speed up the ground motion analysis, but they are applicable only to limited areas for which extensive earthquake data are available. Fortunately, the Sichuan and Yunnan region is such an area. A large body of research work has been done on ground motions produced by Sichuan and Yunnan regional earthquakes, based on both numerical and statistical methods (e.g., Cui JW et al., 2006; Bjerrum et al., 2010; Mao Y and Hu JH, 2012; Ren YF et al., 2014; Meng LY et al., 2014; Zhang ZG et al., 2014; Yao XD et al., 2015).

The degree of earthquake damage to a building depends not only on the maximum amplitude of the ground motion, but also on the height of the building and the frequency of the ground shak-
ing. Low-rise buildings of one or two stories are often affected by ground motions of relatively high frequency (1–2 Hz) and are particularly prone to damage by the so-called Lg wave. The Lg-wave behaves as a distinct seismic phase in the epicentral distance range of 2°–15°. In particular, it can propagate through quite a long distance in the continental crust and thus plays an important role in damage to low-rise buildings due to its relatively large amplitude and rich high-frequency content (Kennett, 1986). To estimate the amplitude of the Lg-wave reliably, an attenuation model needs to be established.

The Lg-wave attenuation structure in the Sichuan and Yunnan region has been studied previously. For example, Zhou LQ et al. (2008) published Lg-wave Q models at different frequencies for this region. In the study presented here, we use a much improved dataset to build an Lg-wave attenuation model with high resolution for the crust of the Sichuan and Yunnan region. Then, based on the approach of Kennett and Wei Z (2017), we use our Lg-wave attenuation model and a given geometrical spreading coefficient to study the propagation of high-frequency ground motions in the Sichuan and Yunnan region. By analyzing characteristics in the distributions of the ground motions produced by regional events, we derive a map showing the degree of damage risk from high-frequency ground motions produced by earthquakes in the region. Finally, we analyze the distribution characteristics of the average energy produced by earthquakes occurring within an extended time period.

2. Data and Method

In this study we adopt the inversion approach of Kennett and Wei Z (2017) and Wei Z et al. (2017) to develop a high-resolution Lg-wave Q model for the Sichuan and Yunnan region. We choose crustal events of magnitudes between 4.0 and 6.2 in the region and use waveforms collected from the data management centers of the China National Seismic Network, the China Earthquake Administration, and the Incorporated Research Institutions for Seismology (IRIS), with event-station distances between 2° and 20°. Before measuring the spectral amplitudes of the Lg waves for different frequencies, we remove some of the events that are very close to each other to avoid data redundancy. In order to ensure the Lg-wave path coverage for the study region, we have also selected stations and events in the surrounding region. Figure 1 shows the distributions of events and stations that we finally selected to use in the inversion of the crustal Lg-wave Q model for the Sichuan and Yunnan region, including a total of 1166 events and 152 stations.

Figure 2 displays several vertical-component seismograms recorded at regional distances from an earthquake of magnitude $M_W$ 6.1 that occurred on May 12, 2008 in the Longmenshan Fault Zone (LMSFZ), one of the moderate aftershocks of the disastrous Wenchuan $M_W$ 7.9 earthquake. The seismograms are filtered between 0.005 and 12 Hz. The Lg waves are signals arriving in a time window defined by the low and high group velocities of 3.0 km/s and 3.6 km/s. They usually have larger amplitudes at regional distances than those of body waves and contain energies of higher frequencies than the later arriving surface waves. At each station, we compute the spectral amplitude of the Lg-wave using the record in the Lg-wave time window, and the spectral amplitude of noise using the record of the same length before the P-wave onset. Only the Lg waves with signal-to-noise ratios (SNR) of 2.0 and larger are used. The spectral amplitudes of the Lg waves are denoised based on the spectral amplitudes of noises (Zhao LF et al., 2010).

We collect the vertical-component Lg-wave records from a large number event-station pairs in order to obtain the Lg-Q model in the Sichuan and Yunnan region. Since the energy of the Lg waves in the Sichuan and Yunnan region is mainly concentrated in the frequency band of 0.3–2.0 Hz, in this study we focus on the Lg-Q model of the same frequency range.

The Lg-Q model is a function of both frequency and location. The attenuation of Lg waves is influenced mainly by the propagation of relatively high-frequency ground motions. The energy of the Lg-wave as measured by the square of its amplitude can be expressed in terms of its Q value as

$$E(f, \Delta) = \frac{E_0}{\Delta} \exp\left(-\frac{2\pi f \int_{ray} dsQ^{-1}(x, y, f)/V\right),$$  

where $E_0$ is the initial energy specified by the earthquake magnitude, $\Delta$ is the epicentral distance, $V$ is the group velocity of the Lg-wave, $x$ and $y$ are the coordinates where the Lg-Q is evaluated, and $f$ represents frequency. Based on Equation (1), we can calculate the frequency-dependent ground motion at any distance from an event given the Lg-wave Q model. On the other hand, using the recorded Lg waves, we can measure their spectral amplitudes to obtain the frequency-dependent energy $E(f, \Delta)$, which can then be used to invert for the Lg-Q model according to Equation (1). The relationship between the earthquake magnitude and initial energy $E_0$ is given by the following equations (Kasahara, 1981; Kennett, 2001):

$$\log E_0 = 5.8 + 2.4M_b$$
$$\log E_0 = 11.8 + 1.5M_w$$
$$\log E_0 = 11.8 + 1.5M_s$$

where $M_b$, $M_w$, and $M_s$ represent the body wave, moment, and surface wave magnitudes, respectively. The energy unit is the erg. We can obtain the initial energy given each of the three types of magnitude.

In using Equation (1), each source-to-station ray path is traced and used to calculate the Lg-wave attenuation along the path. The Sichuan and Yunnan region is seismically very active, with numerous small earthquakes each year and occasional moderate ones of magnitudes 5–6, which provides plenty of observations of Lg-wave attenuation. The number of Lg-wave attenuation can be different at different frequencies. Figure 3 shows the distributions of the available source-station ray paths used to invert for the Lg attenuation model at frequencies of 0.5 Hz, 1.0 Hz and 2.0 Hz. The inclusion of events and stations located outside the study region leads to a very dense distribution of crossing ray paths in our region of interest, which enables us to obtain high-resolution models of the Lg-wave attenuation at different frequencies.

Although the Sichuan and Yunnan region is covered by sedi-
ments, the site amplification effect on seismic waves is not very strong. Furthermore, the azimuthal variation in Lg-wave amplitudes due to source radiation pattern tends to be homogenized beyond ~100 km epicentral distances.

To test how well the dataset of the Lg-wave spectral amplitudes we use can recover the Lg-wave attenuation characteristics in Sichuan and Yunnan region, we conducted a suite of checkerboard resolution tests using checkerboard Q models created from uniform background Q values of 92, 244, and 317 for the frequencies of 0.5 Hz, 1.0 Hz, and 1.5 Hz, respectively, modified by alternating perturbations of the Q value up to a relative absolute amplitude of 7%, as shown in Figure 4. For each frequency, we tested different grid sizes for model parameterization ranging from 0.1° to 1.0° with an increment of 0.1°. In the end we chose 0.7° × 0.7° as the grid size to use in the inversion. In general, the entire study region is well constrained by our dataset, except for areas on the edges where the ray paths are relatively sparse.

3. Lg-Q Model for the Sichuan and Yunnan Region

Figure 5 shows the Lg-Q model in the Sichuan and Yunnan region obtained by the inversions of Lg-wave spectral amplitudes at frequencies of 0.5 Hz, 1.0 Hz, and 1.5 Hz. It appears that there is not a strong frequency dependence in the Lg-Q values in and around the region. Therefore, we may use the average Q value in the frequency range of 0.3–2.0 Hz, as shown in Figure 6, to characterize the high-frequency ground motions in the region (e.g., Wei Z et al., 2017).

The regional variation of the Lg-Q values at different frequencies seems quite consistent. The Lg-Q value varies at different places with the maximum value above 650 and minimum value below 50. Strong lateral heterogeneity can be seen and the pattern shares features similar to the velocity structure in this region (e.g., Liu QY et al., 2014). The western part of the Sichuan and Yunnan area and its neighboring regions have generally lower Lg-Q (high attenuation) than the eastern part, especially in the western part.

Figure 1. Map of the Sichuan, Yunnan, and surrounding regions. Thin black lines are national and provincial boundaries. Thick black lines depict the major fault zones in the region with names in black, including the Longmenshan Fault Zone (LMSFZ); the Xianshuihe–Anninghe–Zimuhe Fault Zone (XAZFZ); the Xiaojiang Fault Zone (XJFZ); the Lijiang–Xiaojinhe Fault Zone (LXFZ); the Jinshajiang Fault Zone (JSJFZ); the Red River Fault Zone (RRFZ); and the Lancangjiang Fault Zone (LCJFZ). Circles and triangles show the locations of events and seismic stations selected for our Lg-Q model inversion. The sizes of circles indicate magnitudes according to the legend. The green filled circle and green triangles show the event and stations whose waveforms are illustrated in Figure 2. The white rectangle marks the study region. Major geological blocks are indicated by texts in green. Major cities are shown by yellow circles with their names in the same color. The grey-scaled background shows the topography.
A sharp contrast in the $Lg$-$Q$ value can be seen across the Longmenshan Fault Zone, with low $Lg$-$Q$ value (high attenuation) in the Songpan–Garzê Block in the west and high $Lg$-$Q$ value (low attenuation) in the Sichuan Basin in the east.

| Station Code | Epicentral Distance (°) | Maximum Amplitude (nm) |
|--------------|-------------------------|------------------------|
| QIH          | 12.3                    | 1739.1                 |
| QXL          | 11.8                    | 6049.4                 |
| CHM          | 11.7                    | 3078.7                 |
| YGJ          | 11.7                    | 10492.8                |
| GGS          | 9.3                     | 15951.4                |
| QZS          | 9.0                     | 14056.3                |
| JNT          | 8.8                     | 5432.4                 |
| ZHC          | 8.6                     | 3410.2                 |
| NNS          | 8.3                     | 14477.5                |
| CZS          | 8.0                     | 13348.6                |
| TSS          | 8.0                     | 4571.8                 |
| WSH          | 7.8                     | 4995.7                 |
| MLA          | 6.4                     | 13270.5                |

Figure 2. Selected vertical-component seismograms for an $M_w$ 6.1 earthquake that occurred on May 12, 2008 recorded by stations in the Sichuan and Yunnan region. Locations of the event and the 13 stations are shown in Figure 1. The event information is listed in Table 1. The waveforms are all in the time window defined by the velocities of 8.0 km/s and 2.0 km/s. The vertical lines in the seismograms mark the arrival times for velocities of 4.5 km/s, 3.6 km/s, 3.0 km/s, and 2.5 km/s. The $Lg$ waves are signals within the window for velocities between 3.6 km/s and 3.0 km/s.

Figure 3. Ray path coverage for the $Lg$-$Q$ model frequencies of (a) 0.5 Hz, (b) 1.0 Hz, and (c) 1.5 Hz. The white dashed rectangle in each panel marks the model region. Thick white lines depict the same major fault zones as in Figure 1, while thin white lines show national and provincial borders.

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value is also generally high in the Yangtze Block. The attenuation of the Lg waves is relatively low across the Red River Fault Zone, whereas along the Xiaojiang Fault Zone the attenuation is among the highest in the region. In addition, the zone of generally high Lg-wave attenuation extends nearly continuously from the Tibetan Plateau in the northwest corner of the study region to the southern end of the Sichuan–Yunnan Rhombic Block, which may be an indication of the existence of a crustal channel flow in this region.

4. Application of the Lg-Q Model in Estimation of High-frequency Ground Motion

The Q model in Figures 5 and 6 reflects the spatial characteristics in the attenuation of Lg waves propagating in the Sichuan and Yunnan region. To evaluate the effectiveness of this model, we invoke the strategy of Kennett and Wei (2017) and conduct a forward numerical simulation using the actual earthquake in Table 1 (24 June 2012, $M_w$ 5.6) and compare the model-predicted Lg-

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**Figure 4.** Resolution tests for Lg-Q inversions for frequencies of (a) 0.5 Hz, (b) 1.0 Hz, and (c) 1.5 Hz. The checkerboard model consists of cells of $0.7° \times 0.7°$ in dimension with background Q values of 92, 244, and 317 in (a), (b), and (c), respectively, and perturbations of up to ±7%. Thick black lines depict the same major faults as in Figure 1, while thin black lines show national and provincial borders.

**Figure 5.** Map of the Lg-wave Q models at 0.5 Hz, 1.0 Hz, and 1.5 Hz. The thick black lines depict the same major fault zones as in Figure 1, while thin black lines show national and provincial borders.
wave energy distribution with the observation. The result is shown in Figure 7.

In making the plot for the observed ground motion distribution in Figure 7a, we collect the vertical-component waveforms recorded at the stations, remove the instrument responses as well as the means and trends, and filter them to the frequency band of 0.3–2.0 Hz. It should be noted that the plot of the observed ground motion distribution in Figure 7a is obtained by interpolation of the values at the available stations. Therefore, the spatial pattern is affected not only by the Lg-Q model but also by the uneven distribution of stations. Furthermore, as stated earlier, the azimuthal homogenization of the Lg-wave amplitude occurs only beyond ~100 km distance from the source. Therefore, in the area closer to the source the Lg-wave amplitude may still be strongly affected by the source radiation pattern. The general spatial pattern of the

Table 1. Information of the moderate events used in numerical examples

| Origin Time (UT) | Latitude (°N) | Longitude (°E) | Depth (km) | Magnitude (MW) |
|------------------|---------------|----------------|------------|----------------|
| 2007-06-02 21:34:59 | 23.07         | 101.02         | 11.6       | 6.1            |
| 2008-05-12 11:11:02 | 31.24         | 103.63         | 11.5       | 6.1            |
| 2008-08-30 08:30:51 | 26.31         | 101.89         | 2.4        | 6.0            |
| 2012-06-24 07:59:35 | 27.73         | 100.75         | 16.8       | 5.6            |
| 2014-08-03 08:30:14 | 27.22         | 103.46         | 28.0       | 6.2            |
| 2014-11-22 08:55:26 | 30.31         | 101.80         | 2.0        | 6.1            |

Figure 6. Map of average Lg-wave Q over the frequency band of 0.3–2.0 Hz. Thick black lines depict the same major fault zones as in Figure 1, while thin black lines show national and provincial borders.
observed Lg-wave amplitude agrees very well with the model prediction in Figure 7b. The ground motion tends to be blocked by the high attenuation zone in Songpan–Garzê Block in the northwestern and along the Xiaojinhe Fault Zone in the southeast. In contrast, Lg-wave energy can propagate more efficiently in regions with lower Lg-wave attenuation, such as the region across the Red River Fault Zone and the Sichuan Basin in the northeast.

The comparison in Figure 7 demonstrates that our Lg-Q model for the Sichuan and Yunnan region effectively captures the ground motion distribution due to earthquakes in the region. Likewise, we can also use the Lg-Q model to carry out numerical simulations to investigate possible ground motions caused by scenario earthquakes (e.g. Kennett and Wei, 2017), especially ground motions of relatively high frequency (e.g. 0.3–2.0 Hz) that are difficult to approximate with elaborate algorithms such as finite difference or finite element methods, but are nevertheless likely to be more damaging to low-rise buildings.

Figure 8 shows the simulation results of high-frequency ground motion distributions for four scenario earthquakes in different regions. Locations of the four simulated earthquakes are taken from past events as listed in Table 1, located near Pu’er, Yunnan; near Chengdu, Sichuan; near Panzhihua on the border between Sichuan and Yunnan; and near Ludian in northeastern Yunnan. For comparison purpose, we use the same magnitude $M_w$ 6.0 for all four scenario earthquakes. To demonstrate the variations of ground motion, we display the distributions of energies calculated using the average Lg-Q model in the frequency band of 0.3–2.0 Hz (Figure 6).

The ground motion distributions in Figure 8 show different patterns according to the locations of the earthquakes, a direct consequence of the regional variation in the Lg-wave attenuation (Figure 6). For the event near Pu’er, Yunnan Province (Figure 8a), the energy distributes more or less evenly around the source in the beginning, since Lg-Q value does not change much in the Pu’er region. Farther away from the source, the Lg-wave propagation appears to be prevented by the two high attenuation zones in the northeast and northwest directions (Figure 6). Energy distribution for the event located on the Longmenshan Fault Zone (LMSFZ, Figure 8b) displays an asymmetric pattern with respect to the LMSFZ and the Lijiang–Xiaojinhe Fault Zone (LXFZ) due to the contrast in the Lg-Q across the fault zones. For the event near Panzhihua (Figure 8c), which is on the border between the Sichuan and Yunnan provinces, the ground motion pattern has an elongated shape trending southwest-northeast, along the zone of lower Lg-wave attenuation. The energy propagates far into the Yangtze Block and the Sichuan Basin in the east, but is blocked by the low Lg-Q region west of the LMSFZ and LXFZ. With regard to the Ludian earthquake in northeastern Yunnan (Figure 8d), the energy travels quite efficiently over a long distance in the north and east directions due to the high Lg-Q values in the Sichuan Basin and the Yangtze Block (Figure 6), while regions of extremely...
low Lg-Q values to the south and northwest of the epicenter effectively prevent the energy from spreading far in those directions. These numerical examples demonstrate the importance of the Lg-Q model in assessing seismic hazards caused by relatively high-frequency ground motions.

Finally, in Figures 7 and 8 we apply the similar practice to estimate the cumulative influence of high-frequency ground motions brought by all the potential earthquakes. For this purpose, we collect all the earthquakes of magnitudes 4.0–6.2 that have occurred in Sichuan, Yunnan and the surrounding regions since 1994. In this study, we assume that all earthquakes are point sources. Therefore, we do not consider large earthquakes (such as the 2008 Wenchuan Mw 7.9 earthquake) to avoid the finite-source effect. Figure 9a shows the epicenters of the 3106 events obtained

Figure 8. Ground motion distributions across the region for four events with the same magnitude Mw 6.0 occurring in different locations including (a) near Pu’er, Yunnan; (b) near Chengdu, Sichuan; (c) near Panzhihua, at the border between Sichuan and Yunnan; and (d) near Ludian, Yunnan. The ground motions are shown by their energies on a base-10 logarithmic scale. Thick black lines depict the same major fault zones as in Figure 1, while grey dashed lines show national and provincial borders.
from the IRIS data management center (http://ds.iris.edu/ds/nodes/dmc/forms/jweed/). The cumulative average high-frequency ground motion distribution is shown in Figure 9b. It is apparent that the spatial pattern is closely related to the rate of seismicity with the highest energies concentrated in the vicinity of the Longmenshan Fault Zone, in the middle of the Sichuan–Yunnan Rhombic Block, near Ludian in northeast Yunnan and in westernmost Yunnan. However, there are also regions with relatively low seismicity that suffer strong ground motion because of high Lg-Q values, such as the Sichuan Basin, the Yangtze Block, and the Yunnan–Burma Block. These regions are clearly more prone to high-frequency ground shaking; efforts should be taken to reinforce their low-rise buildings to prevent possible damages by earthquakes in the future.

5. Discussion and Conclusions
In this study, we have developed a robust Lg-wave attenuation model in the frequency band of 0.3–2.0 Hz for the tectonically active Sichuan, Yunnan, and surrounding regions. Numerical tests show that our Lg-Q model has a resolution of ~0.7°. Comparison with observations from past earthquakes demonstrates the effectiveness of our Lg-Q model in estimating relatively high-frequency ground motions that are crucially relevant to the safety of low-rise buildings.

Generally speaking, tectonically active regions with high heat flow have relatively low Lg-Q values while stable regions often have relatively high Lg-Q values (e.g., Pasyanos et al., 2009; Zhao LF et al., 2013; Sheehan et al., 2014; Zhao LF and Xie XB, 2016; Wei Z et al., 2017; Zhao LF and Mousavi, 2018). Large portions of our model region are tectonically active and are characterized by low Lg-Q values, except the Sichuan Basin in the east and the Yunnan–Burma Block in the south (Figure 6). Nearly all of the major fault zones are located in low Lg-Q regions with high attenuation, except for the Red River Fault Zone which has had relatively low activity in recent times. The Longmenshan Fault Zone represents a sharp contrast between the stable Sichuan Basin with high Lg-Q values and the active Songpan–Garzê Block with low Lg-Q values. This is clearly a result of the contrast across the fault zone in crustal velocities and thicknesses. The Sichuan–Yunnan Rhombic Block, which is experiencing an overall southeastward extrusion as a result of the push from the Tibetan Plateau, is divided by the Lijiang–Xiaojinhe Fault Zone into a northern part with extremely low Lg-Q values and a southern part with a high Lg-Q eastern region and a low Lg-Q zone along the active Xiaojiang Fault Zone. The low Lg-Q zone may also be related to the proposed lower crust channel flow in this region (e.g., Royden et al., 1997; Bai DH et al., 2010; Wei Z et al., 2010).

The Lg-Q model enables us to conduct numerical simulations for scenario earthquakes in the Sichuan and Yunnan region, which can be helpful in making assessments for future seismic hazards. It is worth pointing out that in the numerical simulations we do not take site amplification effects into account, which may affect the details of the patterns only in Figures 7, 8 and 9. Although high ground motions tend to concentrate in places with high seismic activity, regions with higher Lg-Q values can also suffer intensive
ground motion even though they are far away from high seismicity, as shown in Figure 9b. The strong influences of the larger events and event clusters are apparent, such as the along the Longmenshan Fault Zone and areas around Ludian, Panzhihua, Pu’er, and in westernmost Yunnan on the border between Yunnan and Myanmar. On the other hand, there are regions of moderate ground motion in other places, such as a large part of the Sichuan Basin and in southern Yunnan. There may not have been large historical earthquakes, or large earthquakes in adjacent active seismic zones; however favorable conditions for Lg-wave propagation can still cause significant damages to the low-rise buildings in those places.

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References

Bai, D. H., Unsworth, M. J., Meju, M. A., Ma, X. B., Teng, J. W., Kong, X. R., Sun, Y., Sun, J., Wang, L. F., ..., Liu, M. (2010). Crustal deformation of the eastern Tibetan plateau revealed by magnetotelluric imaging. Nat. Geosci., 3(5), 358–362. https://doi.org/10.1038/ngeo930

Bjerrum, L. W., Sørensen, M. B., and Atakan, K. (2010). Strong ground-motion simulation of the 12 May 2008 Ms, 7.9 Wenchuan earthquake, using various slip models. Bull. Seismol. Soc. Am., 100(5B), 2396–2424. https://doi.org/10.1785/0120090239

Boore, D. M. (1983). Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bull. Seismol. Soc. Am., 73(6A), 1865–1894.

Chen, X. F. (1999). Seismogram synthesis in multi-layered half-space Part I. Theoretical formulations. Bull. Seismol. Soc. Am., 89(4), 1291–1327. https://doi.org/10.1785/0120090239

Hartnell, S. H. (1978). Earthquake aftershocks as Green’s functions. Geophys. Res. Lett., 5(1), 1–4. https://doi.org/10.1029/GL005i001p00001

Irikura, K. (1983). Semi-empirical estimation of strong ground motions during large earthquake. Bull. Dis. Prev. Res. Inst., 33(2), 63–104.

Joyner, W. B., and Boore, D. M. (1986). On simulating large earthquakes by Green’s-function addition of smaller earthquakes. In S. Das, et al. (Eds.), Earthquake Source Mechanics (pp. 269-274). Washington: AGU. https://doi.org/10.1029/GM037p0269

Kanamori, H. (1979). A semi-empirical approach to prediction of long-period ground motions from great earthquakes. Bull. Seismol. Soc. Am., 69(6), 1645–1670.

Kasahara, K. (1981). Earthquake Mechanics. New York: Cambridge University Press.
wave Q tomography in and around Northeast China. *J. Geophys. Res.: Solid Earth*, 115(B8), B08307. https://doi.org/10.1029/2009JB007157

Zhao, L. F., Xie, X. B., Wang, W. M., Zhang, J. H., and Yao, Z. X. (2013). Crustal Lg attenuation within the North China Craton and its surrounding regions. *Geophys. J. Int.*, 195(1), 513–531. https://doi.org/10.1093/gji/ggt235

Zhao, L. F., and Xie, X. B. (2016). Strong Lg-wave attenuation in the Middle East continental collision orogenic belt. *Tectonophysics*, 674, 135–146.

https://doi.org/10.1016/j.tecto.2016.02.025

Zhao, L. F., and Mousavi, S. M. (2018). Lateral variation of crustal Lg attenuation in eastern North America. *Sci. Rep.*, 8(1), 7285. https://doi.org/10.1038/s41598-018-25649-5

Zhou, L. Q., Zhao, C. P., Xiu, J. G., and Chen, Z. L. (2008). Tomography of Q_Lg in Sichuan–Yunnan Zone. *Chinese J. Geophys.*, 51(6), 1159–1167. https://doi.org/10.1002/cjg2.1312