Sensors and Materials, Vol. 36, No. 7 (2024) 2783–2801
MYU Tokyo

S & M 3701

Assessment System of Permanent Displacement of Ground Surface Caused by Seismic Rupture due to Active Faults

Yanqiong Liu,[1] Yanwei Wang,[2*] Liye Zou,[1] and Shanshan Liang[1]

[1]China Earthquake Network Center, Beijing 100045, China
[2]Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering, Guilin University of Technology, Guilin 541004, China

(Received January 3, 2024; accepted July 3, 2024)

Keywords: active fault, permanent displacement, seismic activity, model of earthquake occurrence, seismic hazard

Large-scale surface rupture caused by destructive earthquakes causes serious damage to major projects and requires the estimation of the permanent displacement of the ground surface caused by seismic rupture to take effective measures to reduce the effect of disasters. Therefore, in this paper, we propose a system for assessing the permanent displacement of the ground surface due to seismic rupture, which will be applicable to earthquake engineering. The system takes the physical process of earthquake occurrence as the theoretical basis, comprehensively analyzes the seismic activity, seismic geologic environment, fault activity characteristics, tectonic stress field, and GPS observation data, and evaluates the strong earthquake-prone sections of active faults through motion dynamics simulation. Then, referring to the statistical relationships between historical earthquakes, modern earthquakes, and ancient earthquakes, a model of earthquake occurrence is determined. We combine it with the results of seismic hazard analysis and select different methods of evaluating permanent surface displacements caused by seismic rupture at near-fault sites and far-from-fault sites through suitability analysis. We apply the proposed assessment system for example validation and find that the characteristics of the obtained permanent displacement field of the ground surface caused by seismic rupture are basically consistent with actual engineering laws.

1. Introduction

Earthquake damage investigation shows that near-field structural damage is not only caused by ground motion but also by ground surface rupture. With the increase in China's infrastructure construction year by year, especially the South-to-North Water Diversion Project, the West-to-East Gas Pipeline, highway and railway bridges across rivers and canyons, and large-scale tunnel projects across mountains, crossing active faults with high seismic activity is inevitable. Therefore, it is necessary to estimate the permanent displacement of the ground surface due to

*Corresponding author: e-mail: wangyanwei@glut.edu.cn
https://doi.org/10.18494/SAM4880

ruptures across faults to take effective measures to resist permanent displacement and reduce disaster losses. In addition, the current practical application of various types of anti-dislocation components has also contributed to the fact that the permanent displacement of the surface caused by seismic activity, such as ground motion, becomes the seismic force input to engineering structures. Therefore, the estimation of the permanent surface displacement caused by seismic activity on active faults has become a very important topic for earthquake engineering and earthquake resistance and disaster reduction.(1)

Research on permanent surface displacement caused by seismic activity is generally divided into two approaches: empirical statistics and theoretical analysis. There are many research results of empirical statistical methods, most of which focus on the establishment of the relationship between earthquake magnitude and rupture length, rupture width, and dislocation. The classical works on the statistical analysis of permanent displacement are mainly concentrated at the University of Southern California and USGS and are represented by those of Lee and Trifunac,(2) Todorovska *et al.*,(3) Wells and Coppersmith,(4) and Bonilla *et al.*(5) They examined in detail the surface rupture data of earthquakes in the western U.S. and globally and statistically determined the empirical relationships between earthquake magnitude and rupture length, rupture width, rupture area, and maximum displacement for different fault types. The theoretical study of the permanent displacement of the surface caused by seismic activity at active faults generally adopts probabilistic analysis and deterministic analysis methods. Among them, some progress has been made in probabilistic analysis methods, such as by Todorovska *et al.*, who proposed a probabilistic method based on seismic hazards to assess the future permanent displacement of the ground surface triggered by earthquakes occurring on faults.(3) Meanwhile, much research work has been done on applying deterministic analysis methods,(6,7) but it requires the determination of seismic parameters of future earthquakes, fault rupture information, tectonic stress field, and damage criteria for deep geotechnical materials, which limit the application of deterministic methods in engineering.(8)

Both empirical statistical methods and theoretical analysis methods have advantages and shortcomings. In empirical statistical methods, the empirical statistical relationship may have large error in the surface rupture information and thus cannot be applied to all cases. The statistical relationship of earthquake magnitude and fault rupture for China is still immature at present. Similarly, there are two obvious shortcomings in the theoretical analysis methods at this stage: one is the lack of short-term forecasting of earthquakes, and the other is the lack of data on rock materials and fault mechanical characteristics for 1–10 km underground.

In this study, the seismic activity, seismic geological environment, fault activity characteristics, tectonic stress field, and GPS observation data are used as the database for the fault-block motion dynamics simulation used to estimate earthquake-prone sites. The model of earthquake occurrence at the fault is applied, and in combination with the seismic hazard analysis, the maximum magnitude and time of possible future earthquakes are estimated. Then, different methods are selected to estimate the permanent surface displacements caused by seismic activity in the near-fault and far-from-fault sites.

2. Methodology

2.1 Establishment of the assessment system

The core of the research in this paper is the estimation of permanent displacement caused by seismic rupture at active faults, which requires two aspects of research work: first, earthquake parameters, such as the maximum magnitude, possible location, and possible time of the upcoming earthquake must be obtained; second, a reasonable calculation method to estimate the seismic surface permanent displacement of faults must be chosen.

For the determination of seismic parameters, the research idea is to take the existing knowledge and data as inputs and the seismic parameters, *i.e.*, the possible time, location and magnitude of the earthquake, as outputs of certain methods. The ideal situation is to output the ideal result, that is, the exact solution of the three seismic parameters (T, P, and M) are obtained under the premise that the existing knowledge and data are complete. At this stage, the knowledge and data may not be sufficiently complete, so we can only relax the requirements, and the output will be relaxed accordingly so that we obtain the exact solution of certain seismic parameters. If we continue relaxing the requirements, the output will only be the probabilistic solution of the seismic parameters.

The results of seismic parameters and empirical formulas of fault rupture scale and magnitude are combined to estimate the seismic surface permanent displacement near the fault site and away from the fault site using statistical models and numerical simulation methods, respectively, which have been tested to be reasonable. The specific workflow of the assessment system is shown in Fig. 1.

2.2 Motion dynamics simulation based on fault activity characteristics

Here, we mainly determine the possible segments of future strong earthquakes on active faults in the study area, and the specific research method is described in Ref. 9. Taking the fault-block system composed of the main active blocks in the study area and the main active fault zones on their boundaries as the research object, the existing field geological survey data are collected, and the lack of fault parameter data is supplemented through field investigation to establish the geometric model and segmentation model of the main active faults. Combined with the tectonic stress field data, the displacement field or velocity field obtained from GPS observation data is used as the initial constraint condition of the model. The seismic and geological data are used to determine the model parameters, and the rate- and state-dependent friction laws are applied to the fault interface to analyze the correlation characteristics between consecutive strong earthquakes. The numerical simulation of the mechanical and kinematic states before and after a recent continuous occurrence of multiple strong earthquakes in the region is carried out to elucidate the stress triggering law of the first large earthquake on the subsequent large earthquake and to infer the area prone to future strong earthquakes on the active fault.[10,11]

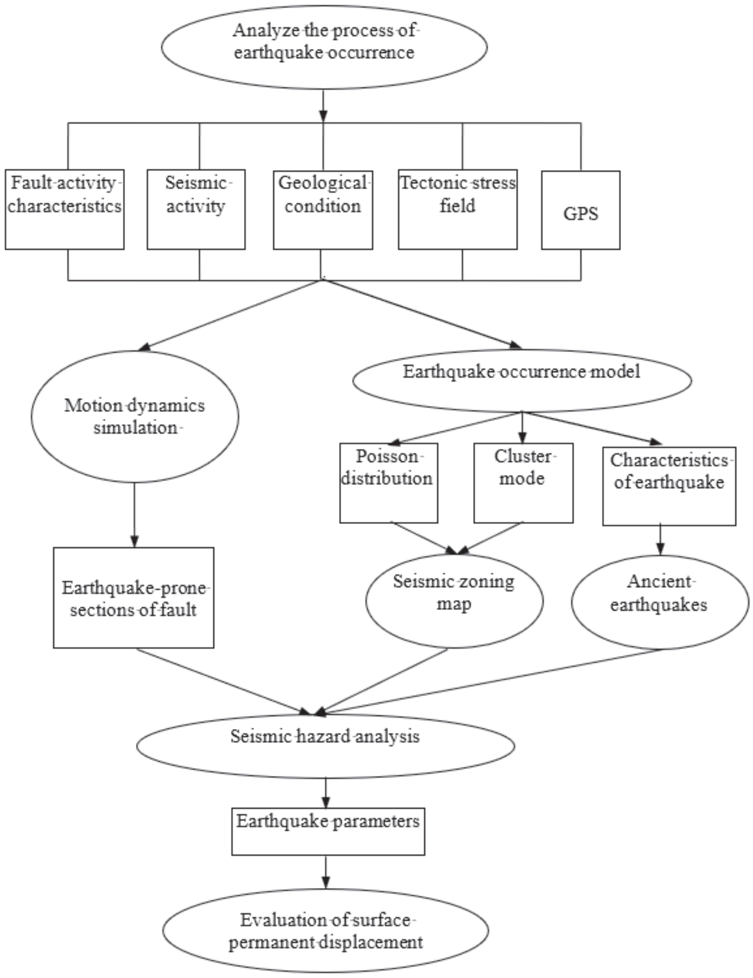

Fig. 1. Process for assessing permanent displacement of surface caused by seismic activity on active faults.

2.3 Model of earthquake occurrence on active fault

The development and occurrence of earthquakes are extremely complex. At the present research level, there is no uniform understanding of the earthquake recurrence law, and whether the Poisson random model, cluster model, quasiperiodic model, or other earthquake recurrence model is used to establish seismic risk calculation and prediction models will directly affect the prediction and evaluation results of seismic hazards.[11,12] Referring to the existing relevant research results, we preliminarily put forward the research methods and steps of establishing the model of earthquake occurrence for a seismic fault.

After obtaining the basic data of seismic activity in each seismic tectonic zone, to study the recurrence behavior of earthquakes, the following research methods and steps are taken. (1) Fault segmentation based on tectonic background and data. (2) Drawing and analysis of the time sequence diagram of seismic activity. (3) Calculation and classification of the earthquake recurrence interval. According to the *M–T* diagram of each segment, the recurrence interval of an adjacent earthquake with surface wave magnitude $M_s \geq 6.0$ is calculated. Depending on the size of the recurrence interval, it is divided into the recurrence interval during the active period and the recurrence interval during the quiet period. (4) Calculation of the normalized data, standard deviation S, and coefficient of variation of various types of earthquake recurrence intervals. (5) Discrimination of recurrent behavior. The calculated normalized data, standard deviation, and coefficient of variation are used to determine the earthquake recurrence behavior on the fault zone. After comparing and analyzing the existing related research, we chose the discriminant method used by Yi *et al.* in their study of strong earthquake recurrence characteristics of active fault zones in the Sichuan-Yunnan area.(13) This method is used to discriminate the overall earthquake recurrence behavior of the fault zone in two cases.

First, without considering the relationship between earthquake intensity and time, a simple point process statistical method is used to determine the earthquake recurrence behavior. When $\sigma < 1$, the recurrence is quasiperiodic. When $\sigma > 1$, the recurrence shows cluster. When $\sigma = 1$, the recurrence is completely random. Second, the intensity–time dependence of the earthquake recurrence process is considered. Separate regression equations are established for each fault zone.

$$\ln T = a + bM_p \tag{1}$$

$$M_l = A + B\ln T \tag{2}$$

T is the time interval between two successive events, M_p and M_l are the magnitudes of the previous and subsequent events, respectively, and a and b or A and B are the regression coefficients.

If Eq. (1) holds, the recurrence behavior is judged to be time predictable; if Eq. (2) holds, the recurrence behavior is judged to be slide (or magnitude) predictable.

The discrimination results of the above two methods are synthesized to determine the earthquake recurrence mode of the fault zone. If the fault zone exhibits the Poisson random mode and clustering mode, the seismic hazard of the fault is analyzed using the parameters of the potential seismic source area of the Fifth Generation Seismic Zoning Map of China. If the fault is characterized by periodicity or quasiperiodicity, the seismic hazard of the fault is analyzed using a characteristic model of earthquake occurrence in conjunction with the determination of the seismic sequences supplemented by data of ancient earthquakes from 10 to 20 thousand years ago.

2.4 Assessment of permanent displacement of surface caused by seismic activity at a near-fault site

We combine the estimation method of the maximum permanent displacement of faults proposed by Lee *et al.*(14) with the seismic hazard analysis method and make full use of the potential source area parameters and fault model of the Fifth Generation Seismic Zoning Map of

China to calculate the maximum permanent displacement of the field points near the active fault under the earthquake scenario corresponding to different exceedance probabilities.(15)

The specific steps of the evaluation method of permanent surface displacement caused by seismic activity at a near-fault site are divided into two cases. If the model of earthquake occurrence on the active fault shows the Poisson distribution or cluster mode, steps (1), (2), and (3) are followed. If the active fault has the characteristics of a periodic or quasiperiodic earthquake, the results of the characteristic earthquake are directly used in the final step (3). The specific steps are as follows. (1) Collect all the seismic geological survey data and seismic activity data of the area where the project site is located and combine the parameters of the potential seismic source area in the fifth-generation seismic zoning map to conduct the seismic hazard analysis of the site. (2) Analyze the results of the above seismic hazard calculations to obtain the equivalent magnitude and epicenter distance of the earthquakes corresponding to different transcendence probabilities, determine the seismic faults near the project site that play a major role in influencing the seismic activity within the project site, and determine the model parameters of the faults. (3) Establish a model for estimating the permanent displacements of the field points near the faults, take the above-determined seismic faults as the research objects, set the magnitude and epicenter distance of the earthquakes or the results of the characteristic earthquakes as the inputs, and then further determine the model parameters and carry out the simulation analysis.

2.4.1 Determination of scenario earthquake

When determining the input parameters of the permanent displacement attenuation model, it is necessary to determine the magnitude and epicentral distance of possible future earthquakes. We can take the characteristic earthquake determined by studying the model of earthquake occurrence in the previous section, or the scenario earthquake based on the seismic hazard probability analysis. In this paper, the maximum probability method is used to determine the specific equivalent magnitude and epicentral distance of the scenario earthquake.(16)

2.4.2 Statistical relationship between rupture and magnitude

In this study, we apply the empirical relationship between rupture scale and magnitude fitted by Wells and Coppersmith, in which global earthquake and all fault type data are used.(4)

$$\log_{10} L_R(M) = 0.59M - 2.44, \sigma = 0.16 \tag{3}$$

$$\log_{10} W_R(M) = 0.32M - 1.01, \sigma = 0.15 \tag{4}$$

Equation (3) is obtained using a subset of data from 167 earthquakes fitted with least squares, and Eq. (4) is obtained using a subset of data from 153 earthquakes fitted with least squares. The magnitude ranges from 4.8 to 8.1.

2.4.3 Permanent displacement attenuation model

To model the permanent displacement near a fault, Lee *et al.*'s model(16) is chosen. The model uses the combined effects of magnitude, epicentral distance, propagation characteristics, different geological units, and local site conditions to evaluate the maximum permanent displacement on the fault.

It is assumed that d_{max} in the model exhibits an averaging property over the rupture length. For an epicenter distance R < 140 km, Lee *et al.* gave the following equation with the unit of cm.

$$\begin{aligned}\log_{10} d_{\max} &= M - 2.2470\log_{10}\left(k / L_R\right) + 0.6489M + 0.518s - 0.3407v \\ &-2.9850 - 0.1369M^2 + \left(-0.0306S_L^1 + 0.2302S_L^2 + 0.5792S_L^3\right) \\ &+\left[-0.3898r - 0.2749\left(1-r\right)\right]R / 100\end{aligned} \tag{5}$$

M is the magnitude, R is the epicenter distance (km), k is the distance from the "representative" source to the site, L_R is the rupture length, and v indicates the direction of motion (v = 0 for horizontal motion, v = 1 for vertical motion). r is the ratio of the horizontal wave passing through the rock. s indicates the site condition (s = 0 refers to sediment, s = 2 refers to rock, and s = 1 refers to site conditions that cannot be clearly classified into either of the first two categories). S_L^1, S_L^2, and S_L^3 indicate site soil conditions related to site soil parameters (S_L^1 = 1 for rocky or hard soil, S_L^1 = 0 for all other cases; S_L^2 = 1 for a thick soil layer, S_L^2 = 0 for all other cases; S_L^3 = 1 for a thick noncohesive soil layer, S_L^3 = 0 for all other cases).

2.5 Assessment of permanent displacement of surface caused by seismic activity for sites far from faults

We combine the principle of Mindlin's analytical formula with the mechanism of seismic surface rupture and apply it to the estimation of the permanent displacement of seismic surfaces.(17) The specific method is as follows.

By applying Mindlin's analytical formula, as shown in Fig. 2, the displacement of any point Q caused by point source P in an elastic half-space is

$$u_i = \frac{(1+\mu)}{8\pi E(1-\mu)} D_{ij} F_j, \tag{6}$$

where E and μ are Young's modulus and Poisson's ratio of the material, respectively.

Now, consider a finite fault model where the fault strike is in the Y direction, the dip is α a, the rupture surface of the earthquake source is an $L \times W$ rectangular plane, and the burial depth of the upper fault point is H_{SD} (see Fig. 3).

For the example of a reverse fault, the rupture property is dip-slip, and the thickness of the fault rupture zone is h (see Fig. 4).

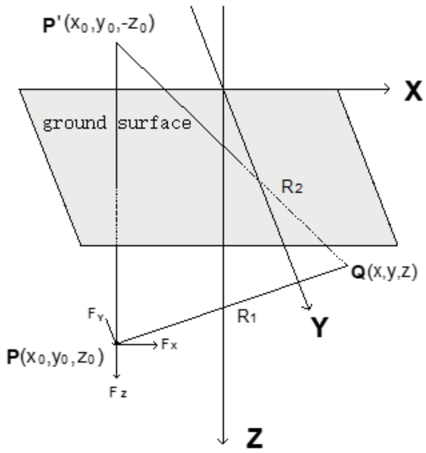

Fig. 2. Point source and coordinate system.

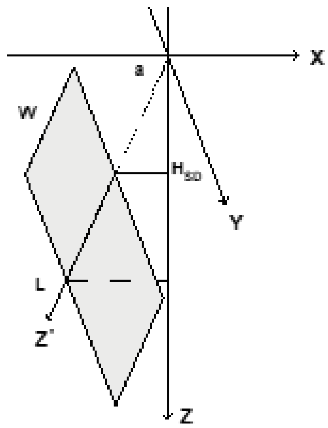

Fig. 3. Finite earthquake source model.

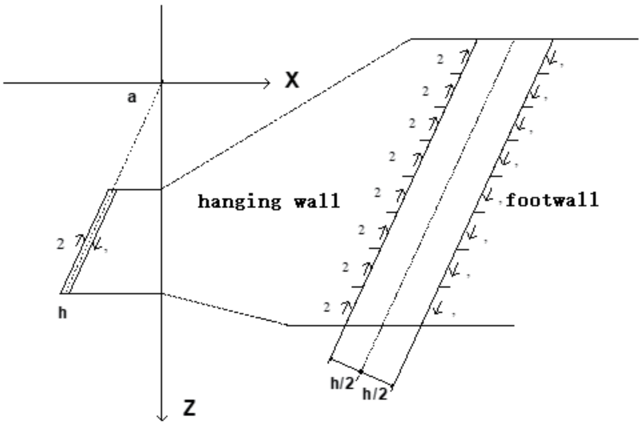

Fig. 4. Distribution of dislocations on the fault plane.

The seismic moment of an earthquake occurring on a fault is M_0, given a subsource M_i (see Fig. 5).

$$M_0 = \sum_i M_i = \sum_i G_i D_i A_i \tag{7}$$

The concentrated force corresponding to the point source couple on the two fault planes is

$$F_j^i = \frac{M_i}{S_j}, \tag{8}$$

where S_j is the quantity associated with h and α.

When an earthquake occurs on a finite fault, the static displacement of any point Q in the elastic half-space is

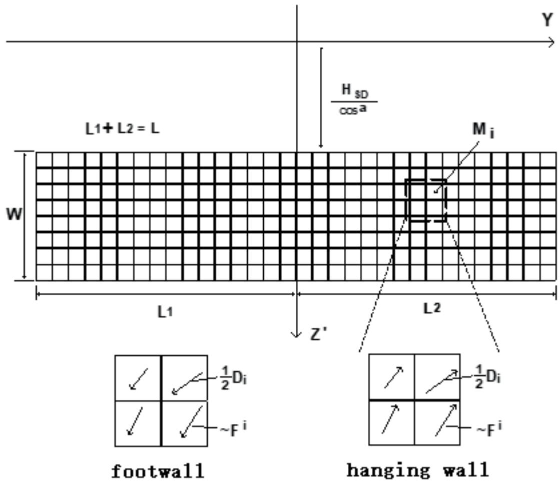

Fig. 5. Subsource delineation of a finite fault plane.

$$u_i = \frac{(1+\mu)}{8\pi E(1-\mu)} \sum_k S_{ij}^k F_j^k. \tag{9}$$

On this basis, the permanent surface displacement field caused by seismic activity is calculated through numerical simulation for sites far from an active fault.

3. Example of Assessment of Permanent Surface Displacement Caused by Seismic Activity

In this study, the Bayankala block and its surrounding Xianshuihe fault zone, Longmenshan fault zone, and East Kunlun fault zone are taken as the study area, and the Dagangshan Dam Project located on the Xianshuihe fault Zone is used as the application background for validation.

3.1 Motion dynamics simulation

The fault-block system composed of the Bayankala block and its surrounding Xianshuihe fault zone, Longmenshan fault zone, and East Kunlun fault zone is selected as the research object. Figure 6 shows the epicenter distribution map of the strong earthquakes in the study area. The movements of the fault-block system before and after the occurrence of recent strong earthquakes in the region, such as the West Kunlun Mountain Pass Earthquake, Wenchuan Earthquake, Yushu Earthquake, and Lushan Earthquake, were simulated, and Fig. 7 shows the modeling of the fault-block system of the study area.

By simulation and calculation, the stress, strain, displacement, and deformation states of the study area were obtained for five stages: before the West Kunlun Mountain Pass Earthquake, before the Wenchuan Earthquake but after the West Kunlun Mountain Pass Earthquake, before

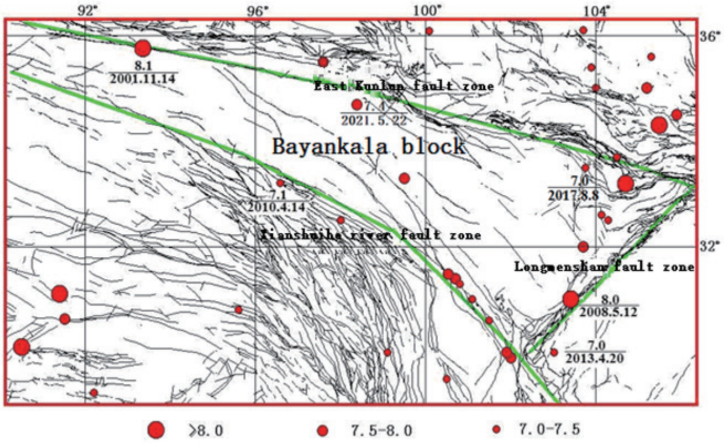

Fig. 6. (Color online) Distribution of epicenters of strong earthquakes of magnitude $M \geq 7$ in the study area.

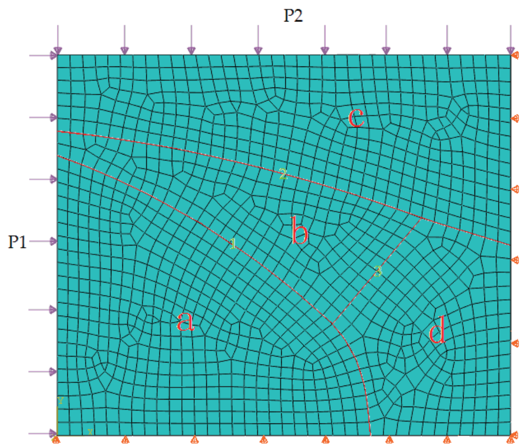

Fig. 7. (Color online) Fault-block model.

the Yushu Earthquake but after the Wenchuan Earthquake, before the Lushan Eearthquake but after the Yushu Earthquake, and after the Lushan Earthquake. Figures 8(a)–8(e) show the von Mises stress cloud maps for these five time periods.

The results show that there may be a certain relationship between the stress, strain, and displacement state and the occurrence of strong earthquakes. The areas with large stress and strain and sudden changes in their distributions are often the areas where strong earthquakes occur. After each strong earthquake, the stress and strain of the fault section will be released, and their distributions will become relatively uniform. From the above rules, it is preliminarily inferred that the areas where strong earthquakes may occur in the Bayankala block and its surrounding areas in the future are the Ganzi-Daofu section of the Xianshuihe fault zone and the southwest and northeast sections of the Longmenshan fault zone.

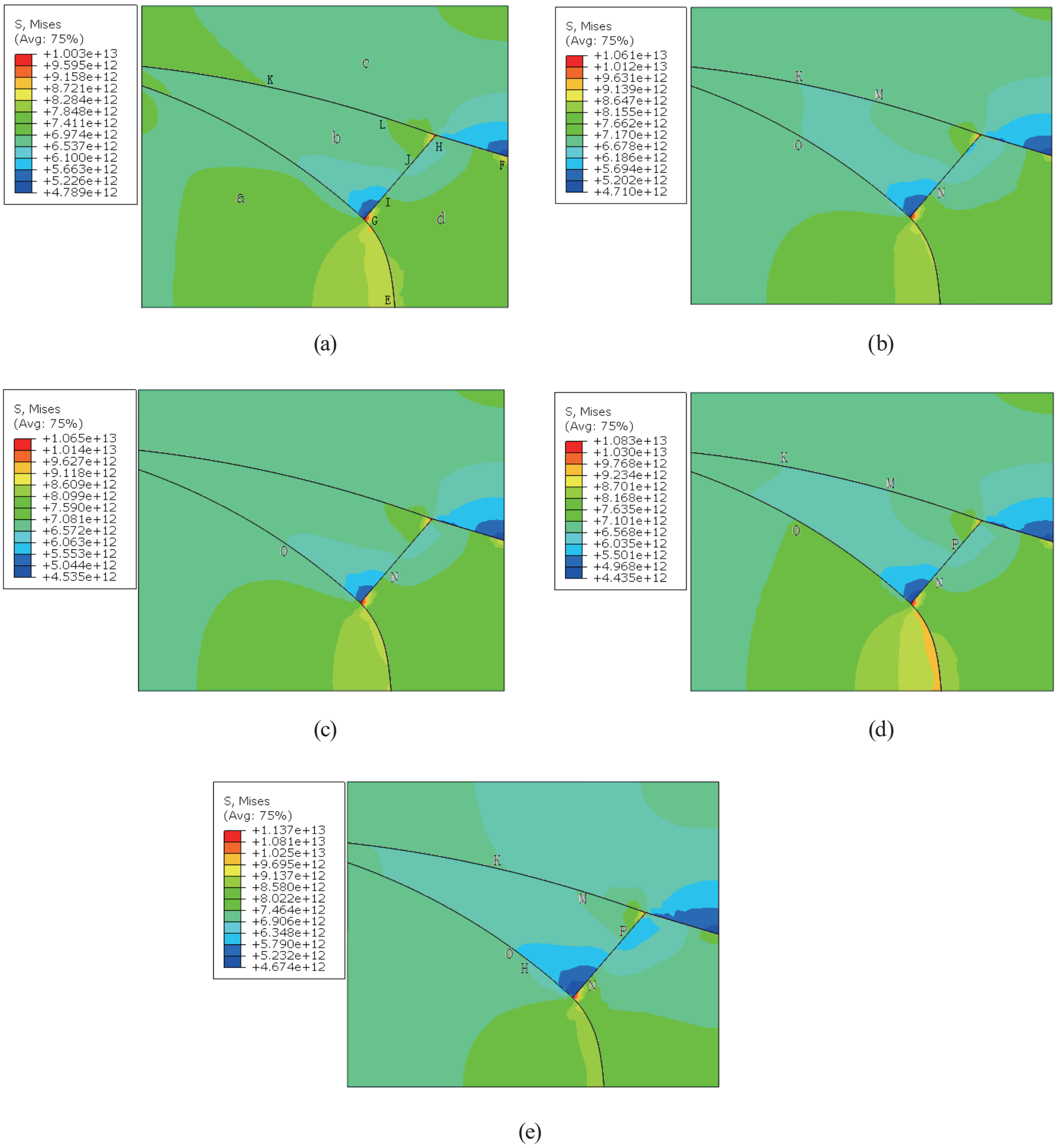

Fig. 8. (Color online) Von Mises stress nephograms of the model. (a) Before the West Kunlun Mountain Pass Earthquake (unit: 10–12 MPa). (b) Before the Wenchuan Earthquake but after the West Kunlun Mountain Pass Earthquake (unit: 10–12 MPa). (c) Before the Yushu Earthquake but after the Wenchuan Earthquake (unit: 10–12 MPa). (d) Before the Lushan Earthquake but after the Yushu Earthquake (unit: 10–12 MPa). (e) After the Lushan Earthquake (unit: 10–12 MPa).

3.2 Determination of the model of earthquake occurrence

From the results of the above work, it is inferred that the northwestern section of the Xianshuihe fault zone is one of the areas where strong earthquakes may occur in the future. Therefore, the model of earthquake occurrence for the Xianshuihe-Xiaojiang fault zone is analyzed. Using the method of determining the model of earthquake occurrence described in Sect. 3, the temporal distributions of earthquakes in the Xianshuihe-Xiaojiang fault zone (Fig. 9), the Xianshuihe fault zone (Fig. 10), and the Xiaojiang fault zone (Fig. 11) are obtained, and the

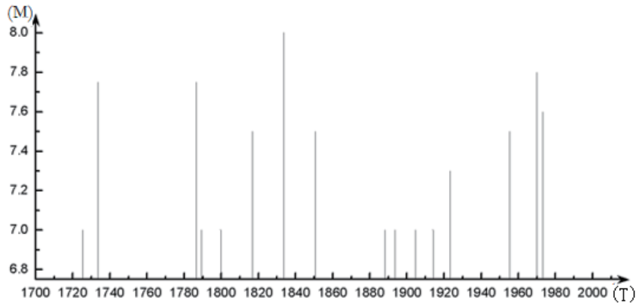

Fig. 9. Temporal distribution of earthquakes with $M \geq 7.0$ in the Xianshuihe-Xiaojiang fault zone.

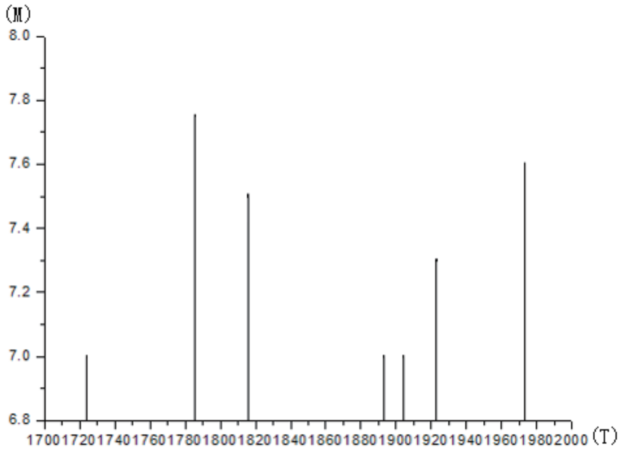

Fig. 10. Temporal distribution of earthquakes with $M \geq 7.0$ in the Xianshuihe fault zone.

Fig. 11. Temporal distribution of earthquakes with $M \geq 7.0$ in the Xiaojiang fault zone.

Xianshuihe-Xiaojiang fault zone is determined to have periodic or quasiperiodic characteristics. The average recurrence interval of earthquakes of $M \geq 7.0$ is approximately 17 years in the whole fault zone, 41 years in the Xianshuihe fault zone, and 58 years in the Xiaojiang fault zone. It is preliminarily determined that the magnitude of the characteristic earthquake is 7 both in the Xianshuihe fault zone and in the Xiaojiang fault zone.

3.3 Estimation of maximum permanent displacement of ground surface

In this study, the Dagangshan dam project located on the Xianshuihe fault is taken as an example for the calculation of the maximum permanent displacement of the ground surface. The Dagangshan Dam is located on the Dadu River in Wajiao Township, Shimian County, Sichuan Province. The geographical coordinates of the dam site are 29°26′49″N, 102°13′02″E. By the above calculation method for scenario earthquakes, it can be determined that the Moxi section of the Xianshuihe fault has the main impact on the site of this project, and the distance between the dam site and the Moxi fault is approximately 5 km. In the near-field range, the spatial location of the dam site and the Moxi fault is shown in Fig. 12.

The magnitude and epicentral distance of the scenario earthquakes corresponding to the 50-year exceedance probabilities of 63, 10, and 2% and the 100-year exceedance probability of 2% are calculated and shown in Table 1. The results are used as the input in the maximum permanent displacement estimation model near the fault examined in this study.

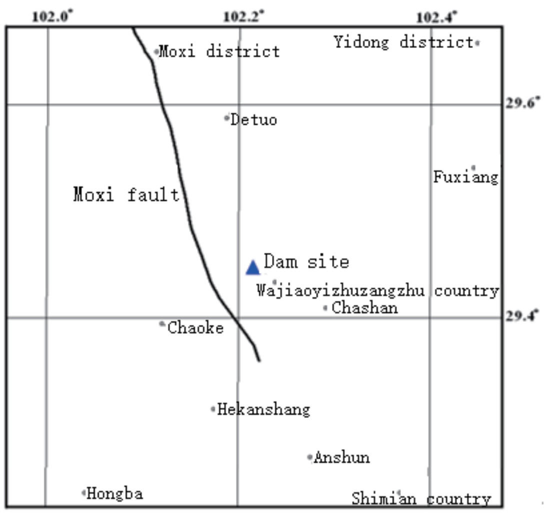

Fig. 12. (Color online) Location map of the dam site and the Moxi fault in the near-field area.

Table 1
Magnitude and epicenter distance of scenario earthquakes with different exceedance probabilities.

Exceedance probability	50 years, 63%	50 years, 10%	50 years, 2%	100 years, 2%
Equivalent magnitude	6.6	7.2	7.5	7.6
Equivalent epicentral distance(km)	62.1	39.9	28.8	25.9

Applying the method described in Sect. 2.3, the curves of the maximum permanent displacement of the ground surface with the epicenter distance at the field points near the Moxi fault under the scenario earthquakes corresponding to different exceedance probabilities are calculated. Figures 13 and 14 respectively show the maximum horizontal and vertical displacements on the fault under the scenario earthquakes corresponding to different exceedance probabilities.

From the results in Fig. 13, it can be seen that the maximum horizontal permanent displacement of the ground surface on the fault is the largest when the epicentral distance is zero. At this time, the maximum permanent displacements on the fault corresponding to the 100-year exceedance probability of 2% and the 50-year exceedance probabilities of 2, 10, and 63% are 937, 806, 490, and 220 cm, respectively. The corresponding maximum horizontal permanent displacements at the field points are 353, 254, 81, and 8 cm, respectively.

From the results in Fig. 14, it can be seen that the maximum vertical permanent displacements on the fault corresponding to the 100-year exceedance probability of 2% and the 50-year exceedance probabilities of 2, 10, and 63% are 422, 364, 221, and 99 cm, respectively. The corresponding maximum vertical permanent displacements at the field points are 161, 116, 37, and 4 cm, respectively.

3.4 Estimation of permanent displacement using the Mindlin solution

The Dagangshan dam project is again used as the example to numerically calculate the permanent surface displacement field of the dam site under a scenario earthquake applying the method introduced in Sect. 2.5.

The determination of the earthquake scenario in this calculation model is the same as in Sect. 3.3. The source parameters of the earthquake are as follows: rupture length is 100 km, rupture width is 18 km, depth of epicenter is 20 km, seismic moment induced by the earthquake

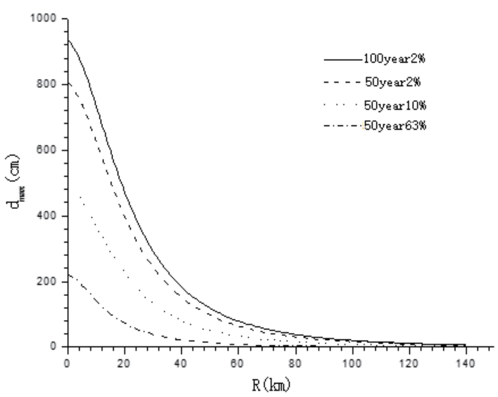

Fig. 13. Maximum horizontal displacements near the fault under the earthquake scenario corresponding to different exceedance probabilities.

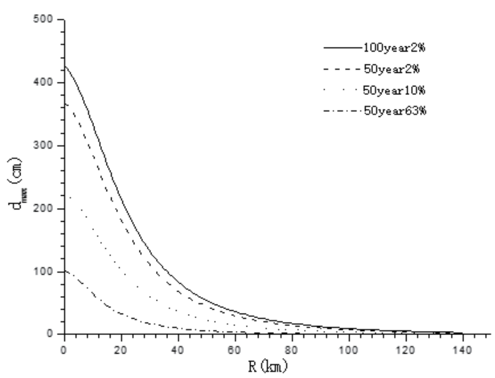

Fig. 14. Maximum vertical displacements near the fault under the earthquake scenario corresponding to different exceedance probabilities.

is 1.985 × 10^{20} J, Young's modulus of the rock body is 3 × 10^{10} Pa, Poisson's ratio is 0.25, and the sliding distribution on the rupture surface is as shown in Fig. 15.

Numerical calculations of the permanent surface displacement field of the dam site under the earthquake scenario were performed to obtain the distribution of the surface permanent displacement field within the limited range of the Moshi fault zone. Figures 16 to 18 show the static displacements on the ground surface in three directions (*x*-direction, *y*-direction, and *z*-direction), and Figures 19 to 21 show the displacement fields on the ground surface in three

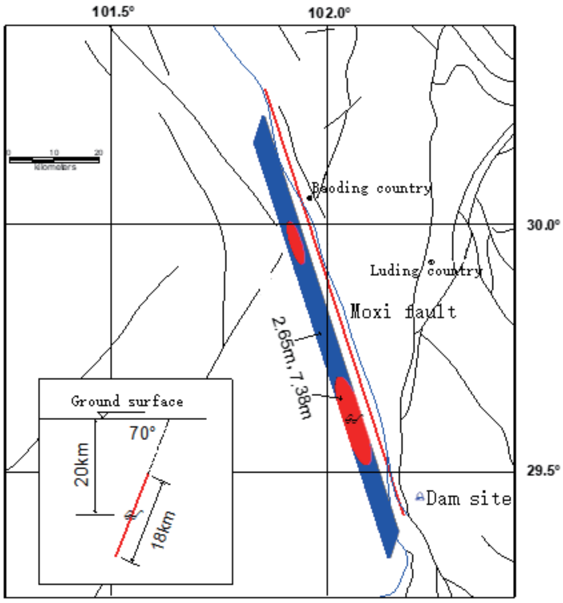

Fig. 15. (Color online) Location of the earthquake scenario and the distribution of sliding amounts.

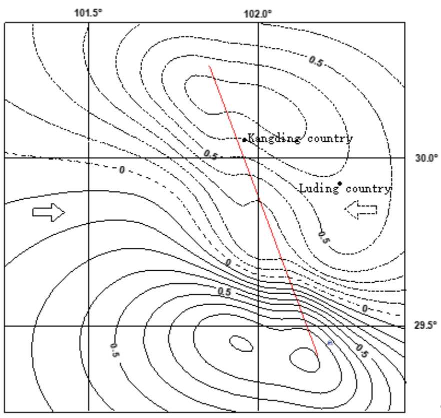

Fig. 16. (Color online) Static displacement field of the ground surface under the earthquake scenario (*x*-direction).

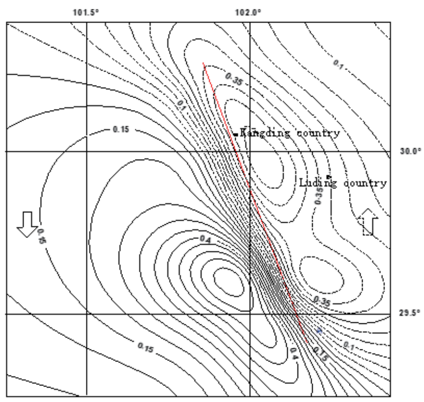

Fig. 17. (Color online) Static displacement field of the ground surface under the earthquake scenario (*y*-direction).

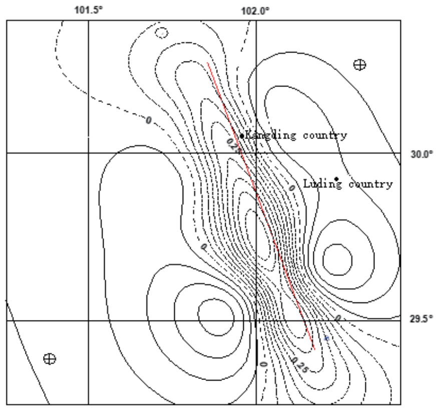

Fig. 18. (Color online) Static displacement field of the ground surface under the earthquake scenario (*z*-direction).

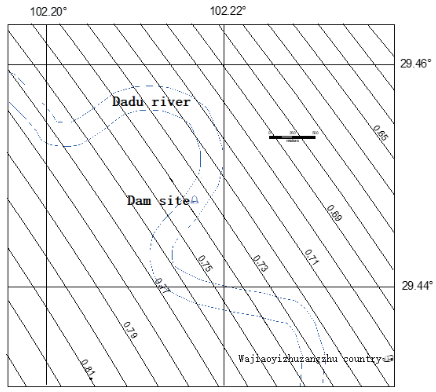

Fig. 19. (Color online) Distribution of the displacement field in the region near the dam site under the earthquake scenario (*x*-direction).

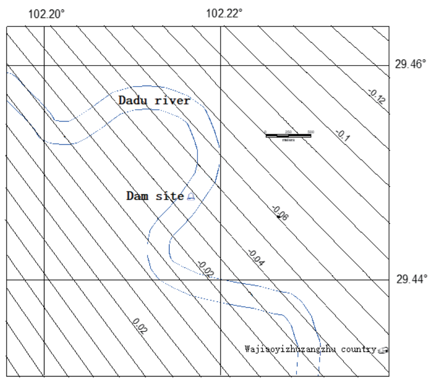

Fig. 20. (Color online) Distribution of the displacement field in the region near the dam site under the earthquake scenario (*y*-direction).

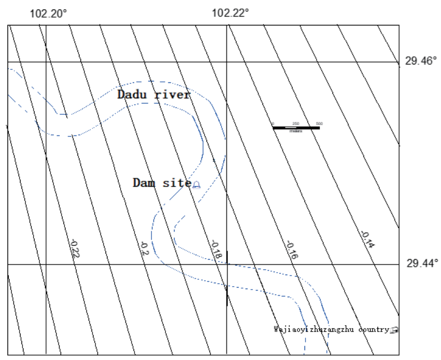

Fig. 21. (Color online) Distribution of the displacement field in the region near the dam site under the earthquake scenario (*z*-direction).

directions (*x*-direction, *y*-direction, and *z*-direction) in a different area near the site. As seen from these figures, the static displacement distribution is relatively uniform at the dam located at a distance of 26 km from the epicenter, and the changes are relatively smooth. The relative displacements of three directions (*x*-direction, *y*-direction, and *z*-direction) with an interval of 100 meters are 1, 1, and 2 cm, respectively.

4. Conclusions and Recommendations

4.1 Conclusions

In this study, active faults and blocks were taken as the research system, and we preliminarily put forward a full process assessment method for permanent surface displacement caused by seismic activity. Using the theoretical basis of the seismic analysis process, we simulated and analyzed the triggering relationship of strong earthquakes in the study area and evaluated the areas prone to future strong earthquakes on active faults. The model of earthquake occurrence was analyzed for the active fault section prone to strong earthquakes, and the possible magnitude and time of occurrence of strong earthquakes in the future were evaluated. On the basis of the seismic parameters determined through suitability analysis, the estimation method of permanent surface displacement caused by seismic activity was selected for the near-field area of the fault (the epicentral distance was less than 140 km). The estimation method based on the Mindlin solution was used to calculate the distribution of the permanent surface displacement field far from the fault. Compared with the previous research results and engineering practice, the results of applying the method in this paper are practical and reliable.(18,19)

4.2 Recommendations

Although the framework of the seismic surface permanent displacement estimation system for active faults has been established, some of the details need to be further improved. (1) The GPS data should be gradually improved, and the real-time GPS displacement field and velocity field data can be used for boundary loading, which may yield more realistic results. (2) The friction constitutive relation related to rate and state can be applied to fault sliding, and it should also be considered whether there is a new friction relationship that is more suitable. In addition, with the in-depth study of important active faults, more detailed and complete fault mud parameters and fault friction characteristics before and after each seismic activity period will be obtained, which will also improve the reliability of the simulation results. (3) The data of active faults in China should be collected, the statistical relationship between fault rupture scale and earthquakes should be established, and the permanent displacement attenuation relationship suitable for the distribution pattern of fault rupture in China should be studied. Through field investigation methods such as trenching, paleoearthquake data of designated active faults should be further collected and the seismic sequence improved to make the prediction of characteristic earthquakes and recurrence intervals more accurate.

Acknowledgments

This research has been supported by the Natural Science Foundation of Guangxi (Grant No. 2023GXNSFAA26226) and the Earthquake Science and Technology Spark Project (Grant No. XH22008B).

References

1 Y. Q. Liu, J. S. Zhao, and Z. G. Zhou: Applied Fundamental and Engineering Sciences **7** (2010) 18 (in Chinese). https://doi.org/10.3969/j.issn.1005-0930.2010.s1.024
2 V. W. Lee and M. D. Trifunac: USC, Report (1995) 95.
3 M. I. Todorovska, M. D. Trifunac, and V. W. Lee: Soil Dyn. Earthquake Eng. **27** (2007) 6. https://doi.org/10.1016/j.soildyn.2006.11.002
4 D. L. Wells and K. J. Coppersmith: Bull. Seismol. Soc. Am. **84** (1994) 974. https://doi.org/10.1007/BF00808290
5 M. G. Bonilla, R. K. Mark, and J. J. Lienkaemper: Bull. Seismol. Soc. Am. **83** (1984) 6. https://doi.org/10.1016/0040-1951(83)90236-6

6 K. Jia, S. Y. Zhou, J. C. Zhuang, C. S. Jiang, Y. C. Guo, Z. H. Gao, and S. S. Gao: J. Geophys. Res. B: Solid Earth **123** (2018) 2965. https://doi.org/10.1002/2017JB015165
7 C. Liu, P. Y. Dong, B. J. Zhu, and Y. L. Shi: J. Geophys. Res. B: Solid Earth **123** (2018) 9963. https://doi.org/10.1029/2018JB015633.
8 J. S. Zhao and Z. H. Zhou: J. Geotechnical Mechanics and Engineering **28** (2009) 3349 (in Chinese). https://doi.org/10.3321/j.issn:1000-6915.2009.z2.009
9 Y. Q. Liu and J. S. Zhao: J. Natural Disasters **24** (2015) 1 (in Chinese). https://doi.org/10.13577/j.jnd.2015.0308
10 G. Luo and M. Liu: J. Geophys. Res. B: Solid Earth **123** (2018) 10968. https://doi.org/10.1029/2018JB015532
11 Y. H. Yang, C. T. Liang, and L. H. Fang: Tectonics **37** (2018) 1648. https://doi.org/10.1029/2018TC005011
12 P. Gong and X. Z. Zeng: Earthquake Research **23** (2000) 57 (in Chinese). https://doi.org/10.3969/j.issn.1000-0666.2000.01.008
13 G. X. Yi, X. Z. Wen, and X. W. Xu: China Earthquake **18** (2002) 267 (in Chinese). https://doi.org/10.3969/j.issn.1001-4683.2002.03.006
14 V. W. Lee, M. D. Trifunac, M. I. Todorovska, and E. I. Novikova: Empirical Equations Describing Attenuation of the Peaks of Strong Ground Motion, in Terms of Magnitude, Distance, Path Effects and Site Conditions, Dept. Civil Eng. Report No. 95-02 (Univ. Southern California, Los Angeles, California, 1995).
15 M. Miyazawa, E. E. Brodsky, and H. Guo: AGU Adv. **85** (2021) 60. https://doi.org/10.1029/2020AV000309
16 J. Dieterich, V. Cayol, and P. Okubo: Nature **408** (2000) 457. https://doi.org/10.1038/35044054
17 Y. Q. Liu and J. S. Zhao: Earthquake Engineering and Engineering Vibration **8** (2014) 212 (in Chinese).
18 Z. Y. Li, J. L. Li, H. j. Yao, and B. S. Wang: J. Geophysics **66** (2023) 1448 (in Chinese). https://doi.org/10.6038/cjg2022Q0035
19 J. He, X. Xu, B. Wu, X. L. Liu, D. H. Yang, T. Lu: Progress in Earthquake Sciences **52** (2022) 97 (in Chinese). https://doi.org/10.19987/j.dzkxjz.2021-078

About the Authors

Yanqiong Liu received her B.S. and M.S. degrees from Harbin Institute of Technology, China, in 2002 and 2005, respectively, and her Ph.D. degree from the Institute of Engineering Mechanics (IEM), China, in 2013. From 2006 to 2018, she was an assistant researcher at IEM, China. Since 2018, she has been a senior engineer at China Earthquake Networks Center. Her research interests are in engineering seismics, strong ground motion observation, and earthquake early warning. (yq_liu@seis.ac.cn)

Yanwei Wang received his B.S. degree from HFUT University, China, in 2004 and his M.S. and Ph.D. degrees from the Institute of Engineering Mechanics (IEM), China, in 2006 and 2011, respectively. From 2004 to 2016, he was an assistant researcher at IEM, China. Since 2016, he has been a professor at GLUT University. His research interests are in earthquake early warning and structure health monitoring. (wangyanwei@glut.edu.cn)

Liye Zou received his B. A. degree from Beijing Normal University, China, in 2001. Since 2005, he has been a senior engineer at China Earthquake Networks Center. His research interests are in earthquake monitoring.
(zouly_xm@qq.com)

Shanshan Liang received her M.S. degree from the Institute of Crustal Dynamics, China, in 2017. Since 2021 she has been a senior engineer at China Earthquake Networks Center. Her research interests are in earthquake location and focal mechanism. (liangshanshan@seis.ac.cn)