# Stochastic Seismic Events Simulation in China Earthquake Catastrophe Model

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## Abstract

Earthquakes are among the most devastating natural disasters in China, causing serious casualties and property losses. To effectively reduce catastrophic risk, it is important to establish an earthquake catastrophe insurance system based on the earthquake catastrophe model, of which seismic hazard analysis is a main module. Probabilistic Seismic Hazard Analysis (PSHA) employs the potential source model, seismicity model and ground motion attenuation model, as well as the probability method to obtain the seismic hazard value of a given point, which represents the comprehensive influence of all future earthquakes thereon. However, as the influence of a single seismic event is required when the earthquake catastrophe model is used for risk analysis, a series of single events needs to be generated according to the potential source model so as to calculate the influence of each event on the given point. In this study, based on the seismicity model (potential sources and their seismicity parameters) used in compiling the fifth generation of Seismic Ground Motion Parameter Zoning Map of China, we use the Monte-Carlo method to simulate a seismic event set conforming to temporal, spatial and intensity distribution of China's seismic activities. In the simulation process, we follow Poisson distribution in occurrence time and the Gutenberg-Richter law in magnitude distribution, and use potential sources and earthquake occurrence rates to describe spatial distribution. The simulated seismic events include the following parameters: time (year, month and day), location (longitude and latitude), depth, magnitude and attitude of seismogenic faults. The simulated seismic event set can support earthquake risk analysis in the earthquake catastrophe model and has been applied in the earthquake catastrophe model of China.

*Keywords: seismic hazard analysis; earthquake catalog; Monte-Carlo; earthquake catastrophe model; earthquake insurance*

# 1. Introduction

As a country with frequent earthquakes, China has suffered from numerous earthquake disasters in history, which have caused huge casualties and great impact on people's life and the social economy. Recent years have witnessed fast development in China's economy, social wealth, with the emergence of a large number of civil engineering projects, which however, have also led to higher social risk levels of earthquakes. It has been of great interest for seismologists, earthquake engineers, sociologists and decision makers to explore and understand the adverse impact of potential earthquake disasters on the society, economy and people's daily life. At present, China relies mostly on government relief after earthquakes in dealing with such risks. With people's growing awareness of self-protection, post-disaster government relief alone can no longer meet the demand, in addition to posing a fiscal burden. Therefore, it is necessary to introduce relevant policies and systems to support multiple parties in playing a more active role in risk sharing, in which the earthquake catastrophe insurance system is one effective means of risk reduction. The purpose of earthquake insurance system is to accumulate earthquake compensation funds for post-disaster reconstruction, and ensure that citizens can quickly rebuild their homes and resume normal life following major disasters [1].

As one important module in establishing an earthquake catastrophe model, seismic hazard analysis mainly includes the probability method and deterministic method, with the former used most widely due to the high uncertainty of earthquake risk. The traditional approach to seismic hazard analysis calculates the influence from all hazard sources point by point, thus covering the comprehensive influence of all hazard sources in its results. In earthquake insurance, the calculation of loss must start with determining the influence field of a single seismic event. In this study, based on the potential sources and their seismicity parameters used in compiling the fifth generation of Seismic Ground Motion Parameter Zoning Map of China, we use the Monte-Carlo method to simulate a seismic event set conforming to China's earthquake catastrophe model. The simulated seismic events can be used to calculate the influence of a single event on the target site, the seismic hazard of multiple sites, as well as the occurrence probability and frequency within specific ground motion parameter ranges, thus able to meet the requirements of risk calculation in earthquake insurance. The following sections will describe in detail the basic model, theories, parameters and stochastic seismic event simulation process used to simulate the event set.

# 2. Potential seismic source model

## 2.1 Zoning of potential sources

In China, scientists have put forward a three-level zoning scheme for potential sources based on latest results and basic data in geoscience research [2]. The following are identified in the zoning scheme: firstly, seismic belts (seismic statistical zones) used for seismicity parameter statistics; secondly, seismotectonic zones (background potential sources) with different seismic features within the seismic belts; and finally, potential sources within seismotectonic zones [2, 3]. The technical approach of this three-level zoning of potential sources properly reflects the spatial unevenness of tectonic and seismic activities in China [2, 3].

In this zoning scheme, these three types of potential sources are spatially superimposed, i.e., the lowest layer represents the largest seismic zone (seismic statistical zones), the middle layer represents tectonic areas of background seismicity (background potential sources), and the uppermost layer, potential sources within seismotectonic areas.

Firstly, seismic belts are determined according to the consistency of seismicity, geology, geophysics, seismotectonics, and geotectonics while considering the adequacy of statistical samples in the earthquake catalog. Seismic belts are also statistical units of seismicity parameters, also known as seismic statistical zones. In addition to identifying the boundary of seismic belts, it is also necessary to determine the upper limit Mu of the magnitude, the *b* value in the G-R relationship and the annual occurrence rate of the earthquake [2, 3, 4 ].


 

Secondly, seismotectonic zones are determined within the seismic belts. Seismotectonic zones are areas demonstrating consistency in seismogenic tectonic model and seismotectonics under the current geodynamic environment [2, 3]. Consistency in seismotectonics means that the properties of seismogenic faults show consistency or similarity under the conditions of the current unified geodynamic environment, deep geophysical field and tectonic stress field. Consistency in seismogenic tectonic model means that seismogenic structures and major events in the same seismotectonic zone can be explained under a unified seismogenic tectonic model, where seismic activities show similar intensity and frequency[2, 3]. The boundary of each seismotectonic zone connects with each other to cover the entire seismic belt. Seismotectonic zones largely reflect the difference in background seismicity in seismic belts, thus are also called background potential sources. They also reflect the spatial differences of seismogenic tectonic models within the seismic belt.

Finally, different potential sources, also known as tectonic potential sources, are determined according to more detailed seismic, geological, geophysical and tectonic data in each seismotectonic zone.

According to the above methods and latest data, Chinese seismologists have identified new seismic belts and potential sources. The whole country is divided into 29 seismic belts and 1643 potential sources (including background sources and tectonic sources) (Fig. 1). Based on the seismicity parameters (earthquake occurrence rate and b value) of the seismic belt, the occurrence rate is assigned to each potential source using the spatial distribution function, thus generating the seismicity model as the basic input for simulating seismic events.

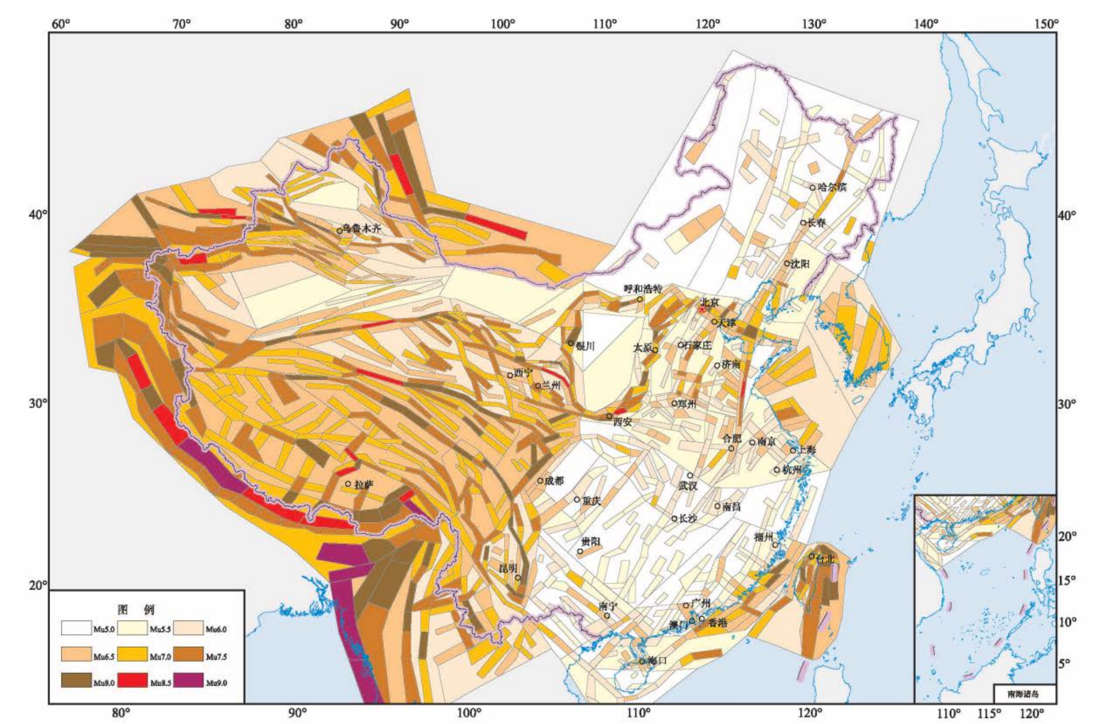


Fig. 1 – Distribution of potential seismic sources in China and adjacent areas [5]

## 2.2 Seismicity parameters

Seismicity parameters include those in both seismic statistical zones (seismic belts) and potential sources.

**Seismicity parameters in seismic statistical zones**

a. Upper magnitude limit *Mu*

The upper magnitude limit in the seismic statistical zone represents the maximum value of potential earthquake magnitude in the area. The probability of the occurrence of an earthquake with the magnitude at the upper limit is almost zero. The upper limit also represents the maximum magnitude value in the Gutenberg-Richter's magnitude-frequency relation in the seismic statistical zone, and is mainly determined by geological structural conditions and historical seismicity.

b. Lower limit magnitude $M_0$

The lower limit magnitude in the seismic statistical zone, also known as threshold magnitude, is the minimum value of magnitude of an earthquake whose influence needs to be considered in the seismic statistical zone. In China, the threshold magnitude is 4.0.

c. *b*-value

The b value of the seismic statistical zone is the coefficient of the G-R relation, which determines the probability distribution of the earthquake magnitude in the area.

d. Annual occurrence rate $\nu_0$ of earthquakes with a magnitude of $M_0$ or above

$\nu_0$, the parameter of the Poisson distribution of the annual number of earthquakes with a magnitude of M0 or above in the seismic statistical zone, also represents the expected value of the annual number of occurrence of the Poisson distribution. It determines the probability distribution of the number of seismic events in the seismic statistical zone. As earthquakes with a magnitude of 4 or above are generally believed to be able to cause damage, the occurrence rate of such earthquakes is calculated in general practice, written as $\upsilon_4$.

Based on the analysis of seismic data and seismicity features in seismic statistical zones, the seismicity parameters in such areas are calculated, with the b values and $\upsilon_4$ of each seismic statistical zone used in this paper shown in Table 1 [5].

Table 1 – Seismicity parameters of seismic statistical zones (seismic belts) [5]

| No. | Seismic statistical zone | *Mu* | *b* | $\nu_4$ |
|---|---|---|---|---|
| 1 | Western Taiwan seismic statistical zone | 7.5 | 0.90 | 22 |
| 2 | Eastern Taiwan seismic statistical zone | 8.0 | 0.92 | 107 |
| 3 | Seismic statistical zone in Middle Reaches of Yangtze River | 7.0 | 1.20 | 3.2 |
| 4 | South China Coast seismic statistical zone | 8.0 | 0.87 | 5.6 |
| 5 | Youjiang River seismic statistical zone | 7.0 | 1.04 | 2.5 |
| 6 | Lower Reaches of Yangtze River-South Yellow Sea seismic statistical zone | 7.5 | 0.85 | 3.0 |
| 7 | Tanlu seismic statistical zone | 8.5 | 0.85 | 4.0 |
| 8 | North China Plain seismic statistical zone | 8.0 | 0.86 | 4.6 |
| 9 | Fenwei seismic statistical zone | 8.5 | 0.78 | 2.5 |
| 10 | Yinchuan-Hetao seismic statistical zone | 8.0 | 0.90 | 4.5 |
| 11 | North Korea seismic statistical zone | 7.0 | 1.05 | 2.0 |
| 12 | Ordos seismic statistical zone | 6.5 | 1.20 | 1.0 |
| 13 | Northeast China seismic statistical zone | 7.5 | 1.00 | 5.0 |
| 14 | West Kunlun-Pamir seismic statistical zone | 8.0 | 0.92 | 50 |



 

| | | | | |
|---|---|---|---|---|
| 15 | Longmenshan seismic statistical zone | 8.0 | 0.71 | 5.2 |
| 16 | Liupan-Qilian Mountain seismic statistical zone | 8.5 | 0.75 | 6.4 |
| 17 | Qaidam Altun seismic statistical zone | 8.5 | 0.84 | 12 |
| 18 | Bayan Har seismic statistical zone | 8.5 | 0.75 | 6.5 |
| 19 | Xianshuihe-East Yunnan seismic statistical zone | 8.0 | 0.85 | 32 |
| 20 | Himalayas seismic statistical zone | 9.0 | 0.85 | 83 |
| 21 | Southwest Yunnan seismic statistical zone | 8.0 | 0.77 | 20 |
| 22 | Central Tibet seismic statistical zone | 8.5 | 0.81 | 25 |
| 23 | South Tianshan seismic statistical zone | 8.5 | 1.1 | 44 |
| 24 | Middle Tianshan seismic statistical zone | 8.5 | 0.80 | 7.0 |
| 25 | North Tianshan seismic statistical zone | 8.0 | 0.83 | 9.0 |
| 26 | Altai seismic statistical zone | 8.5 | 0.75 | 7.0 |
| 27 | Tarim-Alashan seismic statistical zone | 7.0 | 1.2 | 1.6 |
| 28 | South China Sea seismic statistical zone | 7.5 | 1.05 | 6.0 |
| 29 | East China Sea seismic statistical zone | 7.0 | 1.05 | 6.0 |

**Seismicity parameters of potential seismic sources**

The seismicity parameters of potential seismic sources include the upper magnitude limit and the spatial distribution function. The upper limit is mainly determined according to geological data. The spatial distribution function is a parameter assigning the earthquake occurrence rate of the seismic statistical zone to each potential source, and represents the earthquake occurrence probability of the potential source at different magnitudes. Within each seismic belt, the occurrence rate in each magnitude range can be calculated based on seismicity parameters and the G-R relation, and then multiplied by the spatial distribution function of the corresponding magnitude range in the potential seismic source to obtain the occurrence rate in each magnitude range of each potential seismic source in the seismic belt.

The potential seismic source model and its seismicity parameters described above are the main inputs for simulating seismic events, and determine the temporal, spatial and intensity distribution of simulated events.

## 3. Seismicity model and assumptions

Mathematical models of the occurrence time, space and magnitude of earthquakes provide fundamental theoretical basis for seismic event simulation. This section introduces the basic theoretical model of seismic activity and assumptions based on China’s seismic characteristics.

### 3.1 Seismicity model

**Magnitude distribution model:**

The magnitude distribution of earthquakes can be expressed by the magnitude-frequency relation proposed by Gutenberg and Richter [6]:



 

$$\log N = a - bM$$

Where $N$ represents the number of all earthquakes with magnitudes greater than or equal to $M$, and $a$ and $b$ are constants, which can be obtained by regression according to actual earthquake records. The magnitude distribution model is the theoretical basis for simulating earthquake magnitude.

**Time distribution model:**

In probabilistic seismic hazard analysis, we assume that the earthquake occurrence rate per unit time conforms to the Poisson model [7]:

$$P(n) = \frac{(\nu_0)^n e^{(-\nu_0)}}{n!}$$

Where $n$ represents the occurrence frequency of earthquakes per unit time, and $\nu_0$ represents the occurrence rate of earthquakes per unit time calculated according to actual earthquake records. The time series of simulated events can be generated with given time distribution model.

3.2 Basic assumptions

According to the seismological theories above and considering the characteristics of seismic activities in China, we propose the basic assumptions for the temporal, spatial and intensity distribution of earthquakes in China:

(1) The magnitude distribution of seismic activity in the seismic statistical zone conforms to the truncated G-R relationship, and can be written as [8]:

$$N(m) = N(M_0)\frac{10^{-b(m-M_0)} - 10^{-b(M_U-M_0)}}{1-10^{-b(M_U-M_0)}}$$

Where $N(m)$ represents the cumulative frequency of earthquakes with magnitude greater than or equal to $m$, $N(M_0)$ is the number of all earthquakes with magnitude greater than or equal to $M_0$, $M_0$ is the lower magnitude limit, $M_U$ is the upper magnitude limit, $b$ is the slope.

(2) The occurrence time of earthquakes in the seismic statistical zone conforms to Poisson distribution;

(3) The seismic activities in the seismic statistical area are not uniformly distributed among different seismic sources, while the seismic activities in the seismic sources are uniformly distributed..

## 4. Simulation process and seismic parameters

4.1 Technical process

The Monte-Carlo method has been widely used in recent decades in probabilistic seismic hazard analysis[]. The first step of this method is to simulate a random earthquake catalog, and then calculate the seismic hazard accordingly. In this paper, using the potential sources and their seismicity parameters adopted in compiling the fifth generation of Seismic Ground Motion Parameter Zoning Map of China, we use the Monte-Carlo method to generate a random event catalog conforming to temporal, spatial and intensity distribution of China's seismic activities based on relevant theories and hypotheses. The process to generate the main parameters of the simulated seismic events is briefly described in the following flow chart (Fig. 2).



 

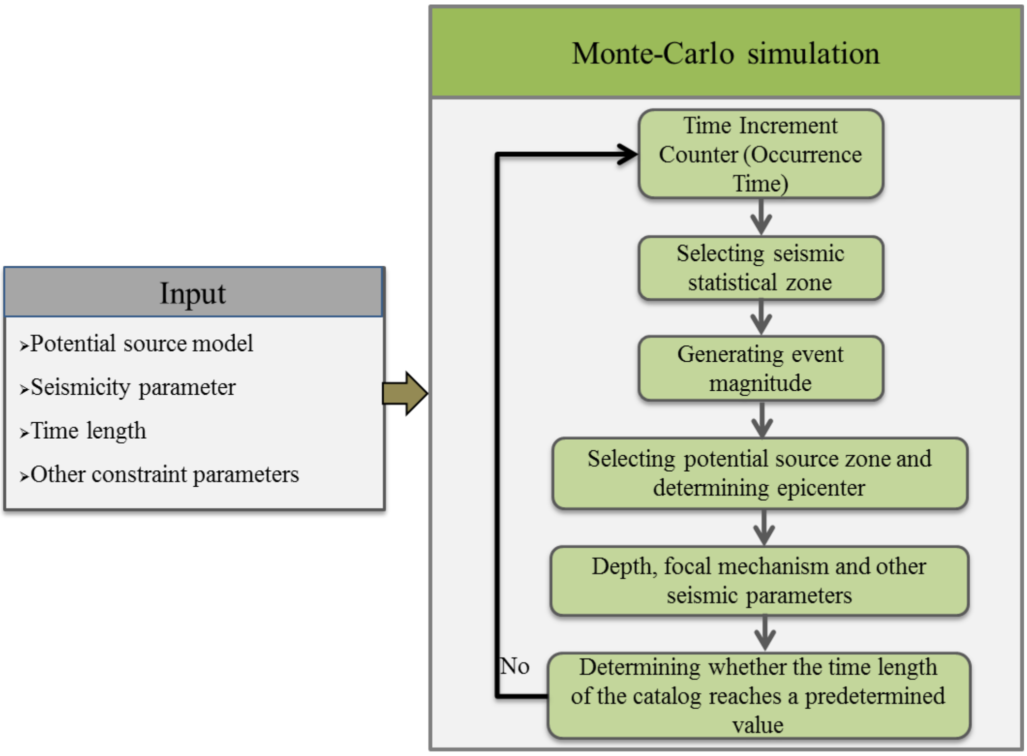


Fig. 2 – Technical process of generation of seismic events

4.2 Time

Time refers to the moment when the earthquake occurs (year, month, day, hour, minute, second). The Working Group sets 1 A.D. the starting time of simulation.

As mentioned above, the occurrence time of the earthquake conforms to Poisson distribution. Once the occurrence rate of the earthquake is known, it can be converted into the expected value of its recurrence period $\lambda$. Then the time interval of earthquake occurrence can be expressed with the following probability density function:

$$f(t) = \lambda e^{-\lambda t}$$

The recurrence interval of the earthquake can be randomly generated according to the probability density function. By accumulating the recurrence intervals of the generated earthquakes, we can obtain the occurrence time of the current simulated seismic event.

4.3 Magnitude

Magnitude measures the size of an earthquake based on the quantity of energy released. The greater the energy released by the earthquake, the greater the magnitude. In China, surface wave magnitude is used to indicate the size of an earthquake, so the magnitude of a generated earthquake is surface wave magnitude. Give the wide application of moment magnitude; surface wave magnitude is often converted into moment magnitude by empirical relationships.

As mentioned above, the magnitude distribution in the seismic statistical zones (seismic belts) conforms to the truncated G-R relationship. Therefore, we first identify seismic belts according to the distribution characteristics of the earthquake occurrence rate, that is, the greater the occurrence rate, the greater the probability for corresponding seismic belts to be selected. After selecting the seismic belt, the seismic magnitude conforming to the magnitude-frequency relationship of the seismic belt can be randomly generated according to the probability density function of the magnitude and the b value of the seismic belt. The probability density of magnitude can be written as:

$$f(m) = \frac{b \ln 10 \cdot 10^{-b(m-M_0)}}{1-10^{-b(M_U-M_0)}}$$

### 4.4 Epicenter

Epicenter here refers to microseismic epicenter, i.e., the projection of the initial point of earthquake fault rupture on the earth surface indicated by longitude and latitude. To identify the potential seismic source where the earthquake falls in after selecting the seismic belt and generating the magnitude, we first calculate the occurrence rate of events in each magnitude range in all potential sources in the previously selected seismic belts, then determine the magnitude range of the generated event, and finally determine the potential source where the event falls in according to the occurrence distribution in that magnitude range. After the potential source is determined, a random point is selected as the epicenter based on the assumption that the earthquake is evenly distributed in the potential source.

### 4.5 Depth

Focal depth is an important seismological parameter related to seismic wave attenuation and plays an important role in the calculation of ground motion influence field. Here, focal depth refers to the distance between the initial point of seismic fault rupture and its projection on the earth surface. The depth of simulated seismic events is mainly determined by the depth distribution of actual records, i.e., the depth of an earthquake that has already occurred is randomly chosen as the depth of the simulated earthquake.

### 4.6 Fault strike, dip angle, type and other parameters

Fault strike refers to the dominant direction of seismic wave propagation, which features relatively slow seismic wave attenuation. In China, fault strike represents an important parameter of Ground Motion Prediction Equations. For certain ground motion prediction equations, the dip and type of the fault are also important parameters. Parameters such as the fault strike of simulated seismic events are determined according to the parameters of the potential source in which the simulated event falls in, i.e., the strike, dip angle and type of fault contained in the potential source are the corresponding parameters of events therein.

### 4.7 Length and width of fault rupture

The length and width of earthquake fault rupture are essential in characterizing the scope of earthquake damage, and are also parameters related to ground motion influence field. The length and width of fault rupture in simulated seismic events are determined according to Wells and Coppersmith's empirical relationships [9].

## 5. Result of simulated seismic events

We generate a set of seismic events with magnitude 5.0 or above in China and surrounding areas based on the above data sources, theoretical model and technical process. The main parameters include time (year and day), location (longitude and latitude), magnitude (surface wave magnitude and moment magnitude), fault rupture direction, fault rupture length and width, attenuation zones, seismic belts and potential sources where events fall in. Table 2 shows the parameter format of the generated event set, among which for the potential source type parameters, 1 represents potential sources within seismotectonic zones and 0 represents background sources; for the focal mechanism parameters, 1 represents thrust faults, 0 represents strike-slip faults, and -1 represents normal faults.

Table 2 – The parameter format of simulated seismic events



 

| AD (Year) | Day | Longitude | Latitude | Depth (km) | Strike (° ) | Dip (° ) | Potential Source Type | Surface Wave Magnitude | Moment Magnitude | Focal Mechanism | Rupture Length (km) | Rupture Width(km) | Seismic Belt No. | Potential Source No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 36 | 121.975 | 23.458 | 16 | 70 | -999 | 1 | 5.96 | 5.83 | -1 | 7.15 | 6.3 | 2 | 30 |
| 1 | 199 | 122.674 | 23.533 | 18 | 70 | -999 | 1 | 6.05 | 5.9 | 1 | 7.57 | 7.14 | 2 | 31 |
| 1 | 342 | 79.605 | 30.388 | 30 | 135 | -999 | 1 | 6.41 | 6.22 | 1 | 11.74 | 9.54 | 20 | 1236 |
| 2 | 26 | 120.934 | 24.669 | 13 | 20 | -999 | 1 | 6.14 | 5.98 | 1 | 8.08 | 8.02 | 1 | 15 |
| 2 | 124 | 78.154 | 35.726 | 38 | 101 | -999 | 0 | 6.5 | 6.29 | -1 | 13.29 | 10.1 | 14 | 819 |
| 2 | 130 | 105.807 | 38.45 | 21 | 160 | -999 | 1 | 6.42 | 6.23 | 1 | 11.9 | 9.6 | 10 | 674 |

To visualize the spatial distribution characteristics of simulated seismic events, we select a 200-year simulated earthquake catalog, and create a spatial distribution map of simulated earthquakes with M≥5. 0 in 200 years (Fig. 4), which demonstrates rather high similarity with the spatial distribution of actual earthquake records. This means that the distribution of simulated earthquakes is able to reflect the uneven spatial distribution of earthquakes in China.

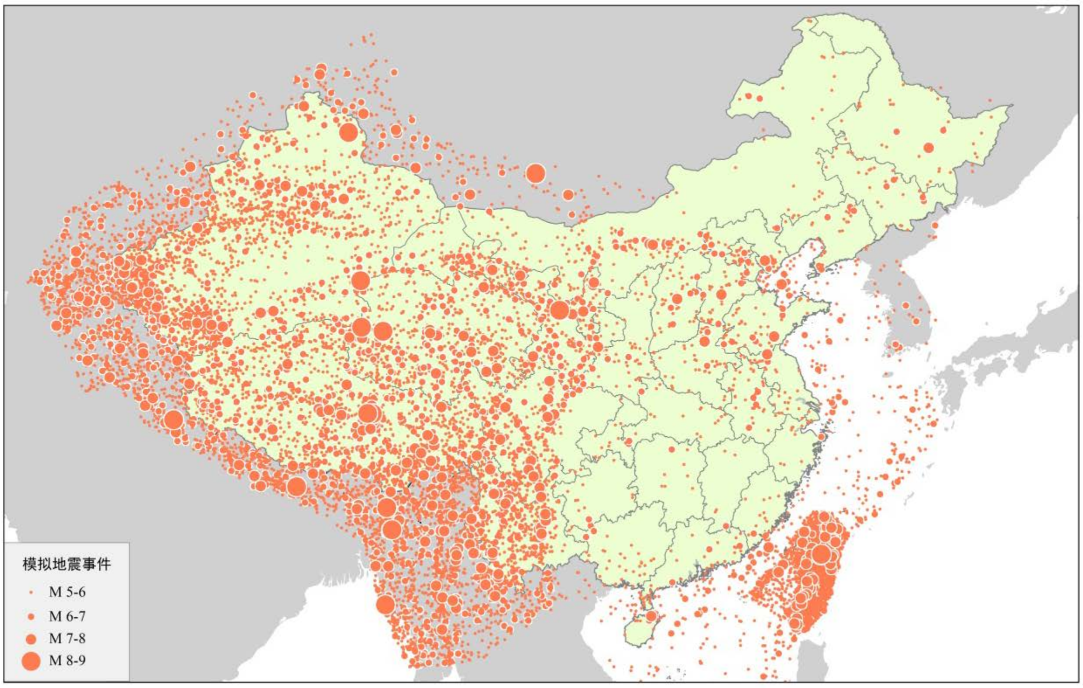


Fig. 3 – The distribution of 200-year simulated seismic events with magnitude equal to or greater than 5.0



 

## 6. Conclusion

Based on the latest version of China's potential seismic source model and its seismicity parameters, this study uses the Monte-Carlo method to generate a simulated seismic event set conforming to temporal and spatial distribution patterns of China's earthquakes. The simulated seismic events include such parameters as time, location, magnitude, depth, strike and attenuation zone. By examining the simulated event set, we find that these events are able to accurately reflect the temporal, spatial and intensity distribution of earthquakes in China. The simulated seismic events obtained in this study can be used for hazard analysis in the earthquake catastrophe model and provide basis for determining earthquake insurance premium rate. This seismic event set has been applied to China's earthquake catastrophe model and provides important technical support for the model.

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## 8. Copyrights



## 9. References

[1] Sun XC. Earthquake risk analysis of rural housing and earthquake insurance demand survey in Yunnan Province. [Ph. D. Thesis][D]. Kunming: Kunming University of Science and Technology, 2018.

[2] Zhou BG, Chen GX, Gao ZW, et al. The Technical Highlights in Identifying the Potential Seismic Sources for the Update of National Seismic Zoning Map of China [J]. Technology for Earthquake Disaster Prevention, 2013, 8(2):113-124.

[3] Gao ZW, Chen GX, Zhou BG, et al. The Principles and Techniques of Identifying Seismotectonic Province in New National Seismic Zoning Map of China——An Example of East China with Middle Seismic Activity [J]. Technology for Earthquake Disaster Prevention, 2014, 9(1):1-11.

[4] Pan H, Gao MT, Xie FR. The Earthquake Activity Model and Seismicity Parameters in the New Seismic Hazard Map of China [J]. Technology for Earthquake Disaster Prevention, 2013, 8(1):11-23.

[5] Gao MT. A handbook of GB18306–2015 Seismic Ground Motion Parameter Zonation Map of China [M]. Beijing: China Standard Press, 2015.

[6] Gutenberg B, Richter C. Frequency of earthquakes in California [J]. Bull Seismol Soc Am, 1944, 34:185–188.

[7] Cornell CA. Engineering seismic risk analysis[J]. Bull Seismol Soc Am,1968, 58:1583–1606

[8] Cornell, C.A. and Vanmarcke, E.H. The Major Influences on Seismic Risk, Proc. of the 4th World Conf. on Earthquake Engineering, Santiago, Chile,1969.

[9] Wells DL, Coppersmith KJ. New empirical relationships among magnitude rupture length rupture width rupture area and surface displacement[J]. Bull Seismol Soc Am, 1994, 84(4):974– 1002.



 