Probability assessment method and application of surface rupture on main controlling fault

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Abstract. This paper summarizes the macro-assessment of meizoseismal ground fracture experience, based on the probabilistic assessment methods described in engineering practice and research status. Earthquake engineering probabilistic analysis is the inevitable result of scientific development, to meet the people's understanding level. Statistics on the Chinese mainland strong ground fracture frequency; proposed a simple method of calculating the probability, and made a spreadsheet. The model uses data primarily from seismic hazard analysis commonly used data, the results are acceptable, the probability model is a simple, easy-to-application features.

1. Introduction

The surface rupture of strong earthquake is also called the ground fracture or dislocation of strong earthquake. It is the ground deformation formed when the seismic fault moves suddenly and the elastic strain can be released to produce strong earthquake, and becomes a window for people to peek into the rupture mode and mechanical properties of the seismogenic fault. It has become a window for people to observe the rupture mode and mechanical properties of the seismic fault. The surface rupture of strong earthquakes is significantly different from the ground deformation caused by sand liquefaction, collapse and landslide. It is strictly controlled by the seismogenic fault, and the exposed position, spreading direction and mechanical properties are consistent with the seismogenic fault, and its damage Huge, non-human can resist.

Strong earthquake surface ruptures have caused widespread concern at home and abroad[3-5]. China’s current code for seismic design of buildings (GB5001-2010) also clearly stipulates the distance to avoid surface rupture of strong earthquakes.

At present, the macroscopic qualitative method is still used for the evaluation method of strong earthquake surface rupture. Engineering practice has proved that the results of macro qualitative evaluation are hardly satisfactory, which goes against the probability concept of earthquake disaster prevention[2] and brings great trouble to the seismic design of the project. Since strong earthquakes and strong earthquake surface ruptures are random natural disaster events, the current scientific level cannot make accurate predictions, and the probabilistic methods are more in line with the current level of understanding.

Therefore, probability assessment is a common requirement in the engineering field. Since the probability of surface rupture of strong earthquakes is lower than that of strong earthquakes, the data is more scarce and it is more difficult to implement probability analysis. There is no successful experience for us to learn from abroad.
China has a large area, many earthquakes, a long time of seismic record and relatively complete data, so it has the advantage of developing probability analysis method. Some scholars [6-10] have begun research on probabilistic analysis methods. On the basis of summing up the experience, based on the experience and data accumulation of the author's many years of seismic hazard analysis, this paper makes an in-depth study on each link of the probability analysis of strong earthquake surface simplification, simplifies its probabilistic analysis method, and initially establishes a strong earthquake. The probability assessment model of surface rupture, combined with the actual situation of the four potential source areas, has been tried and discussed. It is expected to lead the method study to further, finally achieve the purpose of engineering application.

2. Strong Earthquakes and Surface Rupture
The macroscopic experience of surface rupture assessment of strong earthquakes is the basis of its probability analysis, while the probability analysis of surface rupture of strong earthquakes is an extension of the probability analysis of seismic hazard, and the basic data used by the two are consistent.

2.1. Main controlling fault is the main site of strong earthquakes
The occurrence of strong earthquakes is closely related to geological structure. China's seismotectonic distribution map shows that the distribution zones of historical strong earthquakes are distinct [10-12], which is linearly distributed along the main active faults. Statistical results of historical strong earthquakes and seismogenic tectonic sites in China [15] are shown in table 1.

| Seismicity subdivision | M  | Total number of earthquakes | Main faults | Secondary faults | Unknown structure |
|------------------------|----|----------------------------|-------------|------------------|------------------|
| Eastern subdivision    | 6-6.9 | 68                        | 48          | 69               | 17               | 25               | 4               | 6               |
|                        | 7-7.9 | 18                        | 18          | 100              |                  |                  |                 |
|                        | ≥8    | 7                         | 7           | 100              |                  |                  |                 |
| Western subdivision    | 6-6.9 | 267                       | 203         | 76               | 37               | 14               | 27              | 10              |
|                        | 7-7.9 | 86                        | 75          | 87               | 11               | 13               |                 |
|                        | ≥8    | 18                        | 17          | 94               | 1                | 6                |                 |

As can be seen from the statistics in table 1, 100% of earthquakes with magnitude greater than or equal to 7 occur on the main fault in eastern China, 69% of earthquakes with magnitude 6-6.9 occur on the main fault, 25% on the secondary fault, and 6% on the unknown structure. The earthquake occurred in the western subdivision on the main fault, 94% of the magnitude is greater than or equal to 8.0, 87% of 7-7.9, and 76% of 6-6.9. It can be seen that the main fault with strong activity is the main site of strong earthquakes and surface rupture of strong earthquakes, which is also the focus of this paper.

2.2. Statistical characteristics of surface rupture [7-8,10]
The surface rupture of strong earthquakes is the product of strong earthquakes, and strong earthquakes do not necessarily produce surface rupture. Compared with strong earthquakes, surface rupture of strong earthquakes is a lower probability event.

Is a country with a more earthquakes in China, the historical earthquake records can be traced back to the Qin and Han dynasties ago, but the integrity and accuracy of the early data were poor, until modern times, after 1900, roughly as the earthquake instruments and inspect the work gradually thorough, the advent of strong earthquake magnitude, epicenter location and earthquake intensity and earthquake surface rupture more complete and reliable information. In the 100-odd years to 2018, there were 362 earthquakes of magnitude 6 or above on the Chinese mainland, and 34 of them produced surface fractures of different sizes. In general, the situation in China is basically similar to that in foreign countries [3-5], with only a few earthquakes accompanied by surface rupture.

The statistical results of surface rupture frequency of strong earthquakes according to magnitude classification and epicentre intensity are shown in table 2.
Table 2. The statistics on frequency of Chinese meizoseismal ground fracture.

| Magnitude   | Grade interval | Grading Center | Total number | Surface rupture frequency % | Epicenter intensity | Total number | Surface rupture frequency % |
|-------------|----------------|----------------|--------------|-----------------------------|--------------------|--------------|-----------------------------|
|             | 6-6.4          | 6.2            | 206          | 1                           | 0.5                | 7            | 199                         | 0                           | 0                           |
|             | 6.5-6.9        | 6.7            | 95           | 7                           | 7.4                | 8            | 102                         | 2                           | 2                           |
|             | 7.0-7.4        | 7.2            | 40           | 8                           | 20                 | 9            | 38                          | 14                          | 36.8                         |
|             | 7.5-7.9        | 7.7            | 12           | 9                           | 75                 | 10           | 15                          | 10                          | 66.7                         |
|             | ≥8             | 8.2            | 9            | 9                           | 100                | ≥11          | 8                           | 8                           | 100                          |

3. Earthquake yearly average occurrence ratio

Gutenberg-Richter first proposed that the relationship between magnitude and frequency is subject to exponential distribution, and its expression is as follows.

\[ \log N = a - bM \] (1)

Where, \( N \) is the cumulative number of earthquakes with magnitude greater than or equal to \( M \), and \( a \) and \( b \) are regression coefficients. This relationship can well reflect the proportional relation of the distribution of large and small earthquakes. In China's magnitude-frequency relationship between the magnitude of the grading interval train \( m \) (0.5), the statistical unit for the earthquake zone or zone, so as to ensure that there are enough statistical samples. As an important parameter, \( b \) value has obvious influence on the result of probability analysis.

The probability analysis of surface rupture by the above-mentioned strong earthquake is an extension of the probability analysis of seismic hazard, and the basic data used by the two are consistent. Thus, the yearly average occurrence ratio of surface ruptures for strong earthquakes can be expressed in terms of \( \nu_s \). It is important to note that according to table 2 and relevant data that surface ruptures occur rarely below magnitude 6.0, the yearly average occurrence ratio of surface ruptures for strong earthquakes refers to the yearly average occurrence ratio of earthquakes above magnitude 6 in the seismic zone.

Using the probability distribution function \( F(M) \) and probability density function \( f(M) \) of magnitude \( M \), the calculation formula of the yearly average occurrence ratio distribution problem can be further deduced:

\[ \nu_{ij} = \nu_j \omega_{ij} \int_{M_{j-1}}^{M_j} f(M) dM \cdot \omega_{ij} = \nu_j [F(M_j) - F(M_{j-1})] \omega_{ij} \] (2)

With formula (2) it is easy to calculate the yearly average occurrence ratio of the \( i \)-th potential source region, \( j \) magnitude file \([M_{j-1}, M_j]\).

4. A probabilistic model of surface rupture

Strong earthquake surface rupture disaster is a kind of low-probability event with great harmfulness. The macro qualitative assessment can only give the answer of “Yes” or “None” and the possibility of “big” or “small”. Due to the lack of probabilistic meaning, design engineers are faced with a dilemma in decision making. At the same time, the probability prediction of earthquake and strong earthquake surface rupture is in line with the current level of knowledge, which is also very necessary for the seismic engineering. Therefore, the probability assessment method replaces the macro qualitative assessment method is the inevitable result of historical development. Through the above introduction, it is known that based on the seismic hazard, a probabilistic model framework for the surface rupture of strong earthquakes in the main source area can be given.

4.1. Probabilistic model framework

The probability of strong earthquake surface rupture on the main fault in the potential source area can be represented by the formula (3).
In the formula, $M_L$ is the lower limit of magnitude, that is, the minimum magnitude that may cause surface rupture, and the value is 6. $M_U$ takes the upper magnitude limit of the potential source area. The letter symbol $f(R|M)$ as the magnitude of $M$ conditional probability, the earthquake surface rupture induced by a number of factors which affect the conditional probability, such as the source, route of transmission, the geologic site condition factors, etc., these factors to quantify the surface rupture should be broadly representative of conditional probability and reliability, but is very complex in practical quantitative operation needs to be studied in-depth. The letter symbol $f(M)$ is the magnitude probability density function of the evaluated main fault. The probability density value of the seismic region or zone where the potential source area is located can be determined by expert distribution, and it is assumed that the earthquake occurs uniformly on the main fault. If the difference of seismic activity of main fault is obvious, it should be considered when dividing potential source area. If there are several main faults in the potential source area, the spatial distribution function of each main fault should be determined according to the difference of seismic activities, and the annual average earthquake incidence in the potential source area should be reallocated. Due to the low probability of a strong earthquake on the surface of the secondary fault, it is generally not considered.

Experience shows that, the most dangerous earthquake that causes the surface rupture disaster is the site right beneath city-type earthquake[8].

4.2. Simplified probability model

Formula (3) is the integral expression of the probability assessment of surface rupture of strong earthquakes. In the mathematical sense, the integral is the summation. In the engineering sense, $\Delta M$ is not infinitesimal and the interval is $\Delta M=0.5$. After the magnitude $M_L$ and $M_U$ is discretized, Equation (3) becomes a finite number of algebraic sums of several products. Therefore, formula (3) can be expressed in a more concise mathematical form of equation (4).

$$P_R = \sum_{j=1}^{n} \nu_{ij} \cdot R_j$$  \hspace{1cm} (4)

In the formula, $\nu_{ij}$ can be calculated by the formula (2) and $R_j$ is the frequency of surface rupture caused by the earthquake of the $j$ magnitude graded interval, which is obtained from Table 2. The letter $n$ is the number of magnitude graded interval in the potential source area. The magnitude graded interval is $M=6$, and with the interval of $\Delta M=0.5$, 6.0-6.4, 6.5-6.9, 7.0-7.4, 7.5-7.9, 8.0-8.4. The grading center is 6.2, 6.7, 7.2, 7.7, 8.2 in turn. It can be seen that the number of the magnitude graded interval of the potential source area is determined by the upper limit of the magnitude $M_U$, and the $M_U$ changes from 6.5 to 8.5. The number of grades is changed from 1 to 5.

The above analysis shows that the occurrence probability of surface rupture of strong earthquakes can be solved intuitively and simply by using formula (4).

5. A probabilistic model of surface rupture

5.1. Basic parameters

Taking the four potential source regions in the North China earthquake region as an example, the probability of surface rupture of strong earthquakes in these potential source regions is calculated to illustrate the analysis and discussion of the probability analysis calculation process and calculation results.

Table 3 shows the seismicity parameters of four potential source areas, including Tangshan, Sanhe, Huailai and Xinding. The relationship between magnitude and frequency of surface rupture of strong earthquakes is shown in table 2.

The yearly average occurrence ratio of earthquakes distributed by seismic zones to the potential source area is shown in figure 1[13].
Table 3. The basic parameters used in probability calculation.

| Seismic Belt              | $\lg N = a - bM$ | Yearly average occurrence ratio distributed in each potential seismic source area |
|---------------------------|------------------|---------------------------------------------------------------------------------|
|                           |                  | 6.0-6.4 | 6.5-6.9 | 7.0-7.4 | 7.5-7.9 |
| Hebei Plain Seismic Belt  | $a = 2.45$       | 7×10$^{-4}$ | 3.1×10$^{-4}$ | 2.8×10$^{-4}$ | 3.5×10$^{-4}$ |
|                           | $b = 0.62$       | 4.6×10$^{-4}$ | 2.2×10$^{-4}$ | 2×10$^{-4}$ | 4.4×10$^{-4}$ |
|                           | $\nu = 0.933$    | 1×10$^{-3}$    | 1.7×10$^{-3}$    | 1.4×10$^{-3}$    | 1.3×10$^{-3}$    |
| Fei-Wei River Seismic Belt| $a = 2.93$       | 7×10$^{-4}$ | 2.4×10$^{-4}$ | 0.5×10$^{-4}$ | 8×10$^{-4}$ |
|                           | $b = 0.69$       | 4.6×10$^{-4}$ | 2.2×10$^{-4}$ | 2×10$^{-4}$ | 4.4×10$^{-4}$ |
|                           | $\nu = 1.626$    | 1×10$^{-3}$ | 1.7×10$^{-3}$ | 1.4×10$^{-3}$ | 1.3×10$^{-3}$ |

Table 4. Probability calculation results.

| Seismic source area    | Transcendence probability by graded interval | Recurrence period of the surface rupture (year) | 50-year transcendence probability (%) |
|------------------------|---------------------------------------------|-----------------------------------------------|--------------------------------------|
|                        | 6.0-6.4 | 6.5-6.9 | 7.0-7.4 | 7.5-7.9 | $\Sigma$     |                                                |
| Tangshan potential source area | 3.5×10$^{-6}$ | 22.9×10$^{-6}$ | 56×10$^{-6}$ | 262.5×10$^{-6}$ | 3.5×10$^{-4}$ | 2857 | 1.74 |
| Shanhe potential source area | 2.3×10$^{-6}$ | 16.3×10$^{-6}$ | 40×10$^{-6}$ | 330×10$^{-6}$ | 3.9×10$^{-4}$ | 2564 | 1.93 |
| Huailai potential source area | 5×10$^{-6}$ | 125.8×10$^{-6}$ | 280×10$^{-6}$ | 975×10$^{-6}$ | 13.9×10$^{-4}$ | 719 | 6.72 |
| Xinding potential source area | 3.5×10$^{-6}$ | 17.8×10$^{-6}$ | 130×10$^{-6}$ | 600×10$^{-6}$ | 7.5×10$^{-4}$ | 1333 | 3.68 |

According to the yearly average occurrence ratio of the potential source separation grades given in Table 3 and the magnitude-frequency of the strong earthquake surface rupture, using the formula (4), the
Annual transcendence probability of the surface rupture of the strong earthquake occurring at the main faults of the above four potential seismic areas can be obtained, as shown in Table 4. The recurrence period of the surface rupture of a strong earthquake is the reciprocal of the annual transcendence probability, and the 50-year transcendence probability can be calculated by formula (5).

\[ P_t = 1 - \left(1 - P_1\right)^t \]  

In the formula, \( P_1 \) is the annual transcendence probability, \( t \) is the number of years, and \( P_t \) is the annual transcendence probability.

The recurrence period of the surface rupture of a strong earthquake and the 50-year transcendence probability are also listed in Table 4.

5.3. Analysis of calculation results

(1) It can be seen from the calculation results in Table 4 that the contribution of high-magnitude graded interval to the probability result is much greater than that of low-magnitude graded interval, because the magnitude increases from small to large and the frequency of surface rupture of strong earthquakes increases sharply, that is, the probability of large earthquakes accompanying with surface rupture is much greater than that of small earthquakes. This characteristic is consistent with the common understanding of people;

(2) The calculation results are related to the strength of the seismic activity in the seismic zone where the potential source area is located. The stronger the seismic activity is, the higher the seismic frequency is. The larger the yearly average occurrence ratio assigned to the potential source area is, the higher the probability of surface rupture of strong earthquakes is.

(3) The calculation result is closely related to the upper limit of the magnitude of the potential earthquake zone \( M_u \). The smaller the \( M_u \), the lower the probability of occurrence of surface rupture even if the earthquake yearly average occurrence ratio is high. On the contrary, the larger the \( M_u \), the greater the earthquake impact of the high-magnitude graded interval, even if the incidence of earthquakes is low, and the probability of occurrence of strong earthquakes on the surface is also high;

6. Conclusion

Probability analysis and evaluation of surface rupture of strong earthquakes accord with the current research level of engineering earthquake science, and is also a common requirement for seismic fortification of engineering. Therefore, it is an inevitable result of the development of scientific knowledge that probability evaluation method replaces the macroscopic qualitative evaluation method.

(1) China has a large number of earthquakes and relatively complete seismic data. In the third and fourth generation seismic intensity zoning and seismic zoning establishment process, the potential seismic source area and the ground motion parameter choice made in-depth study, in the important engineering site and urban earthquake disaster prevention plan of seismic safety evaluation work, will involve the potential seismic source area and seismicity parameter selection, reflects the current level of understanding, experience and data accumulated have created favorable conditions for strong earthquake surface rupture probability assessment.

(2) In the probability analysis of seismic hazard, there are uncertainties in various links such as potential source division, seismic activity parameter selection and attenuation, and some of the uncertainties are determined by statistical samples. Some links, such as the division of potential sources and the weight coefficients of seismic spatial distribution, are not only related to earthquake and tectonic background, but also associated with expert knowledge ability and subjective judgment. Nevertheless, it is generally acceptable.

(3) Probabilistic models and simplified computational analysis methods proposed in this paper are feasible for the assessment of surface rupture probability of strong earthquakes in potential source regions and main faults. However, it is necessary to consider the influence of various factors in the evaluation of surface rupture of site strong earthquakes.
Acknowledgments
This work was financially supported by National Natural Science Foundation of China (51608118), Hebei Natural Science Foundation (E2017512013). We thank professor SUN Pingshan provided the Surface-Fault-Rupture data. Particular thanks go to Wang qiang careful and thorough inspection of the article.

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