Quantitative Assessment of Seismic Mortality Risks in China

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Abstract: Based on the forming mechanism of seismic hazard risk, we established a seismic vulnerability curve on population and determined earthquake occurrence parameters. We then assessed the risk of seismic hazard mortality at the county level across China using the assessment model, and analyzed spatial patterns. We adopted past, present, and future disaster-breeding materials to assess the probability of earthquakes. In order to determine the earthquake parameters of 2355 counties accurately, we integrated historical seismic intensities, seismic activity fault belts distributions and seismic peak ground acceleration. Based on data of seismic disasters from 1990 to 2009 in China, linear fitting between seismic intensities and mortalities was performed. And a vulnerability curve of seismic mortality, which was appropriate for seismic risk assessment, was established. Seismic mortality risks were assessed quantitatively at the county level using the model and the spatial patterns were analyzed. Seismic mortality risks of 2355 counties with intensities from \textit{V} to \textit{XI} were analyzed thoroughly. This study indicates that under different seismic intensities, China’s eastern and central regions are generally confronted with higher risk than western regions. High-risk areas are scattered in Shandong and Jiangsu, northern Anhui and eastern Heilongjiang and Jilin, where populations are dense and the environment is conducive to disasters. Risk-free areas displayed patchy distributions nationwide, and patterns were mostly unchanged.

Key words: seismic hazards; risk assessment; seismic mortality risks; China

1 Introduction

Earthquakes are sudden natural disasters which can cause serious damage. The damage they cause generally includes building collapse, human casualties and economic losses (Gao \textit{et al.} 2007). The loss of human life is the most significant consequence of earthquakes. It is important to assess seismic mortality risks, because the primary task of earthquake reduction is to reduce human casualties.

It is necessary to predict and estimate earthquake-induced casualties scientifically and then we take appropriate measures that correspond with the possible scale of earthquake casualties. Seismic mortality risk assessment and management has become an important method for effective disaster prevention and reduction, and it has been advocated and promoted widely (Zhang \textit{et al.} 2006). On the background of disaster prevention and reduction, it is necessary to accurately assess seismic mortality risks when the work transferring from disaster emergency management to pre-disaster risk prevention. Seismic mortality risk assessment can provide a scientific basis for disaster prevention and mitigation planning before earthquake occurs, and it can help develop emergency management programs for use during an earthquake and for post-earthquake rescue and relief. It is one of the most important ways to reduce earthquake casualties.

Research into seismic risk assessment began relatively late in China. Considerable research effort has focused on qualitative assessment (Ge \textit{et al.} 2008), but there has been no quantitative computation of seismic mortality risk. Too few studies have been conducted at quantitative or semi-quantitative levels. There are many limitations in the expression of risk results, which are mostly relative levels of risk loss (Anbalagan \textit{et al.} 1996; Shi \textit{et al.} 2006; Zhu \textit{et al.} 2002; Remondo \textit{et al.} 2005; Lee \textit{et al.} 2007; Guzzetti \textit{et al.} 1999; Sarris \textit{et al.} 2009). These analyses of earthquake risk without concrete risk loss values do not reflect mortality differences between earthquakes levels,

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and therefore they do not meet the needs of earthquake prevention and reduction. Under the directions of quantitative assessment, regional integration and spatial management, the primary goal of disaster prevention and reduction work is to determine quantitative risk values and concrete loss from different earthquakes grades.

China is located between the Eurasian and Pacific earthquake belts, and this specific geographical position is responsible for the well-developed fault belts. So China suffers from frequent earthquakes, characterized by great intensities, wide distributions, shallow seismic sources and huge human losses (Wang et al. 2006). According to statistical data recorded by instruments since the 20th century, Chinese earthquakes occupy 33% of global continental earthquakes. There have been thirty earthquakes with a magnitude greater than 5, six earthquakes with a magnitude greater than 6 and one earthquake with a magnitude greater than 7 every year (Pan et al. 2002). In general, there are 210 cities located at intensities ≥6, accounting for 70% of Chinese total cities numbers. But cities with intensities ≥7 occupy only 60% of total cities numbers (Chinese Academy of Building Research 2008). Chinese population base is large, so exposures to earthquakes are vast, and since China is a developing country, the ability to prevent and reduce the damage from earthquake is still limited.

The factors mentioned above highlight that earthquake damages in China are serious and seismic mortality risks are generally high. So our knowledge of risk assessment and emergency prevention is essential for reducing this damage. However, earthquake prevention and reduction work is confronted with many limitations, including unknown distributions of seismic mortality risks, inadequate estimation of disaster situations, improper preparation for earthquakes and lack of pertinence and scientific methods. In order to increase our understanding of seismic mortality risk distributions and promote earthquake prevention and disaster reduction effectively, China urgently needs to quantitatively assess seismic risk. Here we quantitatively assess seismic mortality risks at the county level using the model and then analyze their spatial patterns. This work will provide a scientific basis for Chinese earthquake prevention and reduction.

2 Methodology

2.1 Data sources

2.1.1 Zoning map of county administrative unit
The zoning map of county administrative unit (2004) was provided by the National Geomatics Center of China (NGCC), State Bureau of Surveying and Mapping of China.

2.1.2 Population data
The population data of all provinces at the county level (2008) was provided by the research group. We adjusted the Administrative Map from 2004 to vector map with the actual situation.

2.1.3 Seismic loss data
Considering that populations are continually increasing, an earthquake of the same magnitude in the past may cause many more casualties today. Therefore, when selecting past earthquake cases, those that occurred more recently were preferred. Representatives, timeliness, and the availability of past earthquake cases needed to be considered comprehensively. There are 257 Chinese destructive earthquake catalogs that have been collected and processed mainly from 1990 to 2009 (China Earthquake Data Center [http://www.china-disaster.cn]; Monitoring and Prediction Division of China Earthquake Administration; Disaster Reduction Center of Chinese Academy of Sciences (collected and processed earthquake data (2000–2008), which was published by the National Disaster Reduction Center, Ministry of Civil Affairs of China; National Bureau of Statistics et al. 1995). Using the catalogs, an earthquake database was established for the earthquake loss criteria, which would be useful for calculating a model (Steinbrugge et al. 1969; Chen et al. 1999; Wang et al. 2005).

According to the earthquake data from 1990–2009, there were 12 earthquakes that caused exposures loss each year. There were 3518 fatalities, and 22134 injuries on average and the direct economic loss was 44.381 billion CNY.

2.1.4 Disaster-breeding environment data
The patterns of disaster-breeding environments control earthquake occurrence and distribution. Due to differences in disaster-breeding environments, the probability of earthquakes in different areas is not equal. It is generally believed that areas where earthquakes have occurred or where geological activity fault belts are fully developed will have high probability of earthquakes (Xu et al. 2004; Fang et al. 2002; Xu et al. 2003; Deng et al. 1978, 2002; Chen 1984). Based on the above theoretical analysis, the disaster-breeding environment data consists of seismic faults, past seismic characteristics and seismic fortification level.

(1) Integrated intensities of history earthquakes
In recent years, there were only two destructive earthquakes in Wenchuan and Yushu that had large magnitudes. According to these two earthquakes, the Compilation Committee of National Seismic Zoning developed the first and the second seismic ground motion parameter zoning map of China. Based upon the digital integrated contour map of history seismic intensities (Comprehensive disaster study group of Ministry of Science and Technology, State Planning Commission and State Economic and Trade Commission of China, 2004), we updated the contour map by integrating the
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8.0 earthquake intensity distribution map in Wenchuan (Experts group of earthquake resistance and disaster relief, national disaster-reduction committee and Ministry of Science and Technology 2008) and the assessment map of Yushu earthquake (Restoration and reconstruction group of Yushu earthquake 2010), to reflect the latest achievements of Chinese history seismic intensities (Fig. 1).

(2) Seismic activity fault belts

The seismic activity fault belt distribution map of China (Liao et al. 2000) was spatially overlaid with the Chinese county-level administrative division map. The distributions of seismic activity fault belts in every county were then determined by manual interpretation (Fig. 2).

(3) Seismic peak ground acceleration

Using the seismic peak ground acceleration zonation map of China (State Bureau of Quality and Technical Supervision 2001; Hu et al. 2005), we updated seismic peak ground acceleration by adding zonation maps of Sichuan, Gansu and Shaanxi; Qinghai and Sichuan provinces (Compilation Committee of National Seismic Zoning Map 2008, 2010) (Fig. 3).

2.2 Model method

Risk was defined as expected loss due to a particular hazard for a given area and reference period, given by the combination of disaster intensities and disaster-bearing bodies. Seismic risk was defined as the probability of loss directly provoked by earthquakes, loss that may be suffered by the population, the building and the economic system. It resulted from joint effects between seismic intensities and different disaster-bearing bodies.

Based upon the mechanisms to form seismic risk and by
referring to previous models (United Nations Disaster Relief Organization 1991; Chen et al. 1997, 1999; Wang et al. 2006; Chan et al. 1998; Chen et al. 1998, 2001; Nadim et al. 2009; Zonno 2003), we built the following model and then applied it to assess seismic mortality risks.

\[ R = (D \times E) \times P \]

\( R \) is seismic mortality risk; \( D \) is damaging criteria. It is population susceptibility of different seismic intensities. \( E \) is population exposure of different counties. And \( P \) is the probability of earthquake occurrence.

When applying the model, it was difficult to establish seismic damaging criteria and determine earthquake occurrence probability, which are keys to seismic risk assessment.

2.2.1 Seismic damaging criteria

There are three indexes that can characterize earthquake activity: seismic magnitude, seismic intensity and peak ground acceleration. Earthquake intensity indexes would be screened by processing and analyzing Chinese seismic loss data for 20 years. Compared with seismic magnitude, there is a stronger correlation between seismic intensity and seismic loss (Table 1). We chose to use seismic intensity to characterize earthquake activity.

The best way to establish seismic damaging criteria is to perform physical experiment simulations; but current conditions did not permit these experiments because the earthquake disaster system was extremely complex. By referring to Tangshan seismic mortality (Chen et al. 1994), we established seismic damaging criteria using the data of seismic disasters from 1990 to 2009 in China (Table 2). Exponential curve fitting between seismic intensities and mortalities was conducted (Carrar et al. 2008; Chen et al. 1997), and the vulnerability curve of seismic mortality was established. Its correlation coefficient was 0.8845, which is a good fit.

\[ y = 3 \times 10^5 e^{0.8185x} \]

\( y \) is seismic mortality; \( x \) is seismic intensity.

2.2.2 Earthquake occurrence probability

The occurrence of earthquakes is closely related to geological fault movement, and there exists great differences in seismic activity at different places. In order to determine earthquake occurrence probability, the structure of Chinese geological environments, the distributions of past seismic activity and the latest research information on earthquake prediction and prevention need to be fully considered. We used past seismic activity characteristics, seismic activity faults and seismic

### Table 1 Correlation between earthquake intensity and seismic loss.

<table>
<thead>
<tr>
<th>Pearson correlation coefficient</th>
<th>Mortality</th>
<th>Injury</th>
<th>Homeless</th>
<th>Affected population</th>
<th>Direct economic losses</th>
<th>Building collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic magnitude</td>
<td>0.280**</td>
<td>0.262**</td>
<td>0.517**</td>
<td>0.295**</td>
<td>0.236**</td>
<td>0.322**</td>
</tr>
<tr>
<td>Seismic intensity</td>
<td>0.409**</td>
<td>0.392**</td>
<td>0.564**</td>
<td>0.374**</td>
<td>0.441**</td>
<td>0.468**</td>
</tr>
</tbody>
</table>

Note: ** designates significance at 0.01 significance level (two-tailed test).
fortification levels to determine earthquake occurrence probability.

On the basis of manually interpreting history seismic integrated intensities, seismic fault belt distributions and seismic peak ground acceleration (Figs.1–3, Table 3), the following formula was adopted to calculate earthquake occurrence parameters for every county. For this formula to be effective, several principles needed to be demonstrated, including that places with a strong history of seismic intensity would have a higher probability of future earthquake occurrence, places with seismic activity fault belts would have higher earthquake occurrence probabilities and places with high fortification levels would have higher earthquake occurrence probabilities.

\[ P = \frac{x_1 + x_2 + x_3}{3} \]

\( P \) is the earthquake occurrence parameter; \( x_1 \) is the seismic intensity parameter; \( x_2 \) is the seismic fault belt parameter; and \( x_3 \) is the seismic peak ground acceleration parameter.

The process of determining the parameters was as follows: when \( X_1 \geq A \), \( x_1 = 1 \); and when \( X_1 < A \), \( x_1 = 0 \). If seismic activity fault belts went through the county, \( x_2 = 1 \); otherwise, \( x_2 = 0 \). When \( X_3 \geq A \), \( x_3 = 1 \); and when \( X_3 < A \), \( x_3 = 0 \) (shown in Table 4). \( X_1 \) is history seismic intensity, \( X_2 \) is the distribution of seismic activity fault belts and \( X_3 \) is seismic peak ground acceleration. \( A \) is seismic intensity grates. According to the corresponding relationship between seismic peak ground acceleration and seismic intensity, the parameter of seismic peak ground acceleration can be interpreted (State Bureau of Quality and Technical Supervision 2001). The three parameters were calculated using the formula, and their values were between 0 and 1.

Using Tangshan municipal district as an example, the method of averaging parameters of history seismic integrated intensities, seismic fault belt distributions and seismic peak ground acceleration was adopted to characterize earthquake occurrence probability. This method avoided the problem that earthquakes can’t be predicted accurately. And earthquake occurrence parameters in other counties can be calculated in this method too.

Generally speaking, Seismic intensities of I -IV could not cause casualties, and intensity of VII rarely occur in China. Therefore, we assessed quantitative seismic mortality risks at intensities ranging from X to XI.

3 Results

Based upon the established seismic vulnerability curve and earthquake occurrence parameters, seismic mortality risks were assessed at the county level using the improved assessment model. The seismic mortality risks were mapped to visually illustrate their geographic distribution, and then the spatial patterns were analyzed (Fig. 4).

By analyzing the seismic mortality risk maps, it is apparent that there are great differences between Chinese counties at different intensity levels. With increasing seismic intensity, there is a trend for increasing seismic mortality risk (Table 5).

The spatial distribution patterns of seismic mortality risks were studied and again there are large differences among counties at the same intensity levels. In general, China’s eastern and central regions were confronted with higher risk than western regions.

Generally speaking, high-risk areas had the denser population and the higher earthquake occurrence parameters. They were scattered throughout most of Shandong and Jiangsu, northern Anhui and eastern Heilongjiang and Jilin, where the population is dense and the environment is conducive to disasters.
Risk-free areas showed patchy distributions nationwide, and their distributing patterns were mostly unchanged. They mainly occurred in Guangxi and Liaoning; western Heilongjiang, Jilin, Jiangxi and Xinjiang Autonomous Region; northern Hunan, Guizhou, Shaanxi, Inner Mongolia and Fujian coastal area; and eastern Sichuan Province. The county numbers and their percentages of different risk grades at different seismic intensities are shown in Table 6.

4 Conclusions and discussion

4.1 Conclusions

The quantitative calculation of seismic mortality risk is an important problem, which had not been solved until now. Based on the forming mechanism of seismic hazard risks, we established a seismic risk assessment model, and then assessed seismic mortality risks at the county level. The following conclusions can be drawn from our analysis:

- New assessment methods for seismic mortality risk are feasible, and can provide quantitative seismic mortality risks for all counties. This can greatly improve the original method of risk assessment grades.
- Based on data of seismic disasters from 1990 to 2009 in China, we established the vulnerability curve of seismic mortality, which is the main base to assess seismic mortality risks.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Number</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>146</td>
<td>6.19</td>
</tr>
<tr>
<td>VI</td>
<td>884</td>
<td>3.99</td>
</tr>
<tr>
<td>VII</td>
<td>521</td>
<td>3.04</td>
</tr>
<tr>
<td>VIII</td>
<td>2210</td>
<td>16.54</td>
</tr>
<tr>
<td>IX</td>
<td>266</td>
<td>3.14</td>
</tr>
<tr>
<td>X</td>
<td>698</td>
<td>6.98</td>
</tr>
<tr>
<td>XI</td>
<td>922</td>
<td>9.10</td>
</tr>
</tbody>
</table>

Table 6 Statistics of seismic mortality risks from V to XI.
• We used past, present and future disaster-breeding materials to determine earthquake occurrence probabilities. In order to calculate earthquake parameters of all Chinese counties accurately, we integrated history seismic intensities, seismic activity fault belt distributions and seismic peak ground acceleration.

• Seismic mortality risks were assessed quantitatively at the county level using the model and the spatial patterns were subsequently analyzed. Seismic mortality risks for 2355 counties from V to XI were thoroughly determined. According to the assessment results, the total seismic mortality risk for an earthquake intensity of the V degree is 1 958 685, the VI degree is 3 844 289, the VII degree is 5 617 770, the VIII degree is 7 450 337, the IX degree is 12 475 701, the X degree is 25 045 992 and for the XI degree the total seismic mortality risk is 53 380 705 (Table 5).

This study presented new methodology for risk analysis and assessment of seismic disaster. The methodology employed in this study can be applied to quantitative study of risk from other disaster-bearing bodies (Chen et al. 1997), and natural disasters (Anbalagan 1996; Lantada et al. 2010).

4.2 Discussion

Risk values this paper obtained should not be considered as precise predictions of future loss but rather as estimations of loss, which were assessed by using the risk model according to the forming mechanism of seismic risk. The assessment results are relatively rough, only considering situations that there’s no prediction before earthquake or public awareness of disaster prevention and reduction is low.

In earthquake disasters, there are a number of factors that affect the number of casualties, including seismic intensity, occurrence time, anti-seismic performance of buildings, regional population, public awareness of disaster prevention and reduction, response and action capacity for different individuals and rescue measures (Sun et al. 1993). Seismic casualties are the integrated result of many factors. Only seismic intensity was considered in this paper and a regression curve between mortality and intensity was established to assess the risk. If the correction coefficients of other factors can be determined, the assessment results will be more accurate, and the number between risk and actual seismic mortality will be much closed (Sun et al. 1993).

In order to determine earthquake occurrence probabilities, most risk assessments are conducted based on historical earthquakes reoccurring (Wang et al. 2005), which are often incomplete. We used past seismic activity, seismic activity faults and seismic fortification levels to determine earthquake occurrence probability because they are more scientific and reasonable.

Although the assessment results were relatively rough, they could meet the basic need for Chinese earthquake prevention and reduction. We can identify areas with high seismic mortality risk, and prioritize the allocation of resources and the development of life insurance in these areas. According to results, we can take some actions in advance. For example, in these high-risk areas, we should reduce population exposures and so on. Finally, we can achieve the goal of reducing the number of future deaths.

References


中国地震灾害人口死亡风险定量评估

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摘要: 基于地震灾害风险形成机理, 在建立人口震害脆弱性曲线与确定地震发生参数的基础上, 本文利用评估模型对我国Ⅴ-Ⅺ地震烈度下各县域单元的人口死亡风险进行评估并分析其空间分布格局。主要研究内容有: (1) 首次采用基于过去—现在—未来的多方面地震孕灾环境资料来处理地震发生的可能性。具体综合历史地震综合烈度、地震活动断裂带分布、地震动峰值加速度三方面来确定全国2355个县域单元的地震发生参数; (2) 利用1990-2009年我国历史地震灾情数据, 对地震烈度与人员死亡率之间进行线性拟合, 建立适合我国地震灾害风险评估的震害人口死亡脆弱性曲线; (3) 利用震害风险评估模型对我国各县域单元的人口死亡风险进行定量评估, 并分析风险空间分布格局, 彻底摸清Ⅴ-Ⅺ地震烈度下我国各县域单元的地震灾害人口死亡风险。

研究表明: 在不同地震烈度下, 我国广大的东、中部地区面临更高的风险, 而西部的人口死亡风险相对较低。高风险区域呈零星状分布于山东与江苏大部、安徽北部、黑龙江与吉林东部等人口分布较密集且孕灾环境发育完备的区域。而无风险区域在全国范围内呈斑块状散布, 分布格局基本保持不变。

关键词: 地震灾害; 风险评估; 人口死亡风险; 中国