



A dasymetric data supported earthquake disaster loss quick assessment method

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A dasymetric data supported earthquake disaster loss quick assessment method for emergency response in China

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Abstract

Improving earthquake disaster loss estimation speed and accuracy is one of key factors in effective earthquake response and rescue. The presentation of exposure data by applying a dasymetric map approach has good potential for addressing this issue. With the support of 30'' × 30'' areal exposure data (population and building data in China), this paper presents a new two-phase earthquake disaster loss estimation method for emergency response situations. This method has two phases: a pre-earthquake phase and a co-earthquake phase. In the pre-earthquake phase, we pre-calculate the earthquake loss related to different seismic intensities and store them in a 30'' × 30'' grid format, which has four stages: determining the earthquake loss calculation factor, gridding possible damage matrixes, the building damage calculation and the people loss calculation. The dasymetric map approach makes this possible. Then, in the co-earthquake phase, there are two stages of estimating loss: generating a theoretical isoseismal map to depict the spatial distribution of the seismic intensity field; then, using the seismic intensity field to extract statistics of disaster loss from pre-calculated loss estimation data to obtain the final estimation results. The method is validated by four actual earthquakes that occurred in China. The method not only significant improves the speed and accuracy of loss estimation, but gives spatial distribution for the loss, which will be effective in aiding earthquake emergency response and rescue. Additionally, related pre-calculated earthquake loss estimation data in China could serve to provide disaster risk analysis before earthquakes happen. Currently, the pre-calculated loss estimation data and the two-phase estimation method are used by the China Earthquake Administration.

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1 Introduction

An earthquake is one of most serious natural disasters in the world. For example, the 1994 Northridge earthquake in the USA caused USD 12.5 billion insurance losses (NRC, 1999); the Bam earthquake in Iran (2003) resulted in more than 30 000 deaths (Nadim et al., 2004); 69 227 people died and 17 923 people were lost in Wenchun earthquake in China (2008) (China Earthquake Administration, 2010). Unfortunately, accurate earthquake prediction is still a difficult and even impossible task. In such situations, post-earthquake emergency response and rescue services have been used in many real earthquake scenarios to mitigate the disaster in China. These have already proven their efficiency many times in earthquake disaster mitigation (Earthquake Emergency Rescue Department, 2004). Many real earthquake rescues have shown how prompt and correct decision-making about rescue countermeasures are crucial for success. Since more than 72 h after an earthquake, the survival ratio of the people buried in destroyed buildings sharply decreases, the period after the earthquake has been known as the “golden 72 h” (Xu et al., 2013). Generally, after a destructive earthquake, it is necessary to bring in rescue teams from outside the disaster area, and it will take much time (generally more than two days) for them to gather, be dispatched and to move in, especially in mountainous areas.

Quick and effective rescue decision-making is based on understanding the disaster information, even if it is not very accurate disaster information. However there is a “black-box effect” of co-earthquake and post-earthquake disaster information, which means it is almost impossible to obtain useful disaster information within the first 1 to 2 h after an earthquake (Nie et al., 2012). As an alternative, descriptive earthquake parameters (i.e. earthquake magnitude, peak ground acceleration – PGA) have been used as inputs to estimate the possible losses and provide emergency disaster information, in which possible building damage and loss of life are the most important information.

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China is a country that suffers from serious earthquake disasters. Due to its large land territory and high population, the Chinese government has very high real-time requirements for co-earthquake disaster loss estimation (especially people loss). Generally, it takes only 30 min for experts from the China Earthquake Administration (CEA) to estimate the disaster loss and prepare suggestions on the rescue countermeasures (Miao et al., 2004). Even for a huge earthquake like the Wenchuan earthquake ($M_s = 8.0$), the first earthquake loss estimation and rescue countermeasures should be submitted to the central government within one hour of the earthquake. However, performing the current earthquake disaster loss estimation methods used by the CEA needs more than twenty minutes, not including the time for the rescue countermeasure suggestions and other unexpected actions. Moreover, sometimes the accuracy of the estimation results even cannot correct to an order of magnitude by making comparisons with real disaster information. This has even delayed and misled the rescue decision-making in the response to China's Wenchuan earthquake. As the one of most serious disaster areas, Qinchuan County could not give an appropriate rescue response, while most of rescue materials were sent to Dujiangyan City, where less loss occurred. One of reason for this problem is that the disaster exposure data (population, buildings) are based on administrative units (census tracts).

A dasymetric map approach considers the spatial disparity of disaster exposure data and can improve the disaster estimation accuracy (Chen, 2004). With the support of our former project, a dasymetric exposure dataset (including population, building) has been developed. This study is focused on using these dasymetric data to improve the speed and accuracy of co-earthquake disaster loss estimation (building damage and people loss). This research work is part of the National Key Technology R&D Programme of China entitled, "Earthquake Disaster Information Service and Emergency Decision-making Support Platform". The project aims to develop rapid disaster information estimation and collection methods, and to dynamically generate emergency countermeasures for all levels of government.

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The remainder of this paper is organized as follows: Sect. 2 presents research related to the study; Sect. 3 introduces the areal exposure data that will be used in this study, including population and building data covering the whole of China; Sect. 4 presents a two-phase earthquake disaster loss estimation method based on areal exposure data, consisting of the pre-earthquake phase and co-earthquake phase; Sect. 5 uses four real earthquake cases to validate the speed and accuracy of loss estimation with this estimation method, and discusses the results; and, Sect. 6 sets out the conclusions of this study.

2 Related research

Earthquake disaster loss estimation and risk analysis are key components of disaster management. From an approach fitted to the spatial range, the earthquake damage estimation model can be classified into a globally used model and locally used model. The globally used model tries to estimate the earthquake disasters occurring over the whole world. A Prompt Assessment of Global Earthquakes for Response (PAGER) system has been developed by the US Geological Survey (USGS) to rapidly estimate possible the deaths and economic losses from an earthquake (<http://earthquake.usgs.gov/earthquakes/pager/>). This system can report economic losses and the affected people and the risk level within 30 min of a significant earthquake (magnitude more than 5.5). However, the estimated disaster loss accuracy is reduced by inaccurate information on the shaking caused by the quake because of the spatial variability of the ground motion (Karimzadeh et al., 2014). Similar global (regional) systems are the Global Disaster Alert and Coordination System (GDACS; <http://www.gdacs.org>) and the World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR; <http://www.wapmerr.org>), while the Global Earthquake Model (GEM; <http://www.globalquakemodel.org>) aims to provide software and tools for seismic risk assessment and loss estimation through a worldwide public-private partnership.

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Generally, because earthquake loss estimation is a complex issue, different methods and parameters are needed for different areas of the world (Karimzadeh et al., 2014). Several local earthquake loss methods have been developed by different scientists. Hazards United States Multi-Hazard (HAZUS-MH) is a well-known system (model) developed by Federal Emergency Management Agency (FEMA) in the USA. It can be used for multiple categories of natural disasters, including earthquakes. HAZUS-MH uses a building fragility curve to estimate possible damage, which is supported by census tract data. It is also a time-consuming system to use. The preparation of rapid loss estimates for large study regions of 1000–2000 census tracts might require 0.5 to 1.5 h of analysis time (FEMA, 2003). The Karmania hazard model is another GIS-based local earthquake disaster loss estimation method developed in Iran (Hassanzadeh et al., 2013).

Concerning the disaster estimation methods, many studies have focused on building damage estimation. However, people loss information is more important for earthquake emergency responses. Different levels of people loss mean different response and rescue levels, according to the *Chinese Earthquake Emergency Response Plan* (http://www.gov.cn/yjgl/2012-09/21/content_2230337.htm). However, actual earthquake disaster loss investigations during twentieth century have revealed that 75 % of deaths come from building damage (Coburn and Spence, 2002). So generally, people losses are estimated by regression on building damage estimates. With regard to building damage estimation, two kinds of method are widely used: the destructive probability matrices (DPM) method and the fragility curve method. Whitman (1973) first suggested the use of DPM to describe the building damage probability in earthquakes. It was first adopted by the Applied Technology Council (ATC-13) in 1985 (ATC, 1985). This method firstly classifies buildings into 36 types and this was later reduced to six types in ATC-21 (Mocormack, 1997). In this method, the building damage was classified into five categories: no damage, slight damage, moderate damage, serious damage and collapse. The building damage ratio for different damage degrees (e.g. slight damage, moderate damage) under different seismic intensities are presented as a matrix of the area struck

by an earthquake. The fragility curve method is actually the transform DPM, which use a fragility curve to represent the possible damage related to ground movement parameters.

There are three ways to obtain an appropriate DPM or building fragility curve: an empirical approach, an analytic approach and a hybrid approach. The empirical approach is based on statistics of real earthquake building damage and the setting up of a relationship between earthquake parameters (i.e. PGA, seismic intensity) and the degree of building damage (Anagnos et al., 1995). In the analytic approach, the DPM (or the building fragility curve) is derived from the mechanical analytic calculation for different types of building (Dymiotis et al., 1999). The hybrid approach simultaneously uses seismic hazard investigation data and building structure simulation analysis data to generate the DPM (or building fragility curve; Kappos et al., 2006).

Nowadays, the application of GIS is a growing trend and even a requirement for building damage estimation. The GIS is widely used to manage and analyse disaster exposure data (Mebarki et al., 2014; Panahi et al., 2014; Armenakis, 2013; Alam et al., 2013). Organization of the exposure data in GIS has significant influence on loss estimation speed and accuracy. Chen et al. (2004) and Thieken et al. (2006) elaborated the possible improvement in disaster loss analysis that can be obtained by the application of a dasymetric mapping approach in theory (a brief explanation is given in Fig. 7 to make this paper self-support from the perspective of its application in the earthquake disaster). As one of measures of exposure, there are many discussions about areal population production. Jia et al. (2014) used the dasymetric approach to disaggregate population census data into a quadrilateral grid composed of 30 m × 30 m cells covering Alachua County, Florida. Alahmadi et al. (2013) produced a downscale population distribution of Riyadh, Saudi Arabia using remote sensing data and ward-level census population data. According to Thieken et al. (2006) there are four categories of method for generating population dasymetric map using land cover data: the binary method, the three-class method, the limiting variable method and regression method.

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Accompanying the dasymetric map generation modelling studies, there are already some well-known areal data sets of the world's population, such as the Gridded Population of the World (GPW; Balk and Yetman, 2004), the Global Rural Urban Mapping Project (GRUMP; CIESIN, 2004), the LandScan Global Population Databases (Dobson et al., 2000) and the WorldPop project (<http://www.worldpop.org.uk/>). The data scale generally ranges from 30'' cells (longitude and latitude is 30'', which is about 1 km at the equator) to 7.5'' cells (about 250 m). On the whole, the studies have focused on dasymetric map algorithms; namely, how to generate a dasymetric map and how to improve the data spatial scale (Langford, 2007; Martin, 2011; Lin, 2011; Dmowska and Stepinski, 2014) and most studies have acknowledged the promising potential for applying these maps in disaster risk analysis and mitigation (Chakraborty et al., 2005).

By integrating the above studies and using areal exposure data, we will explore an earthquake disaster loss assessment method for application in Chinese mainland earthquake emergency response, with the aim of improving the speed and accuracy of estimation.

3 The input data

Earthquake disaster exposure data is the foundation of disaster loss estimation. From the perspective of an earthquake emergency in China, these data have been named "earthquake emergency foundation data", which refers to the comprehensive data for earthquake disaster response and rescue including a wide range of social, economic, population, city map, natural geographic landforms, key object location, rescue team information, relief communication and earthquake preplanning data (Nie et al., 2002). Over the last ten years, there has been much progress in the construction of earthquake emergency foundation data. Nowadays, all of the Chinese provinces have built an earthquake emergency foundation database. Currently, the development trend is earthquake emergency foundation data gridding (disaggregated from administra-

tion units to areal grids), with the most popular representation of the data being the 30'' × 30'' cell size (about 1 km at the equator, which we abbreviate it as km grid).

With the support of project "Earthquake Emergency Foundation Data Spatialization and Regional Emergency Response Ability Estimation", Institute of Geology, China Earthquake Administration (CEA) and Institute of Geographic Sciences and Natural Resource Research, Chinese Academy of Sciences (CAS) jointly developed earthquake emergency foundation dataset in km grid format in 2010. In 2013, the dataset was updated with the census data of the year 2011. The whole dataset includes the Chinese mainland in its spatial range and has twenty thematic features, such as population, building and GDP. For this study, our aim was earthquake loss assessment including the estimation of building damage and deaths; therefore, only the km grid format of population data (Fig. 1a) and building data (Fig. 1b–e) were used in this study, as shown in Fig. 1. The buildings were categorised into four types:

- B1 type building (see Fig. 1b): steel and steel reinforced concrete structure, i.e. high-rise steel structure, frame-shear wall structure, high-rise shear wall structure and multi-storey frame or high-rise frame structure. This type of building has the best anti-seismic capacity.
- B2 type building (shown in Fig. 1c): brick masonry structure; this type of structure is widely used in Chinese cities, its anti-seismic capacity is inferior to B1 type buildings.
- B3 type building (shown in Fig. 1d): brick house, open-space structure with 24 mm brick, cavity brick wall structure.
- B4 type building (shown in Fig. 1e): adobe houses mostly in Chinese rural villages. They have the worst anti-seismic capacity.

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4 Two-phase earthquake disaster estimation method supported by km grid format exposure data

Our estimation method consist of two phases: a pre-earthquake phase and a co-earthquake phase. For the pre-earthquake phase, we pre-calculated earthquake loss according to earthquake description parameters and stored the pre-calculated loss estimation data in the database in km grid format. This means the earthquake loss was pre-estimated before it occurred according to appropriate scenario earthquake parameters. Having the exposure data in km grid format makes the disaster loss pre-calculation possible. Then, when the earthquake occurs, the disaster estimation becomes the extraction and statistics from the pre-calculated loss estimation data with regard to the range of its spatial influence. Generally, the studied method will go through two phases and then six stages, as shown in Table 1.

4.1 Pre-earthquake phase

4.1.1 Determination of earthquake losses calculation factor

There are many parameters of the depiction of earthquake movement for disaster loss estimation, namely, surface wave magnitude (M_s), PGA, shaking map and spectral displacement (SD) (Eleftheriadou and Karabinis, 2011). Two factors were considered when we determined the calculation parameters of this study:

1. Availability: our investigation aimed to estimate earthquake disaster loss for the purposes of emergency response. The parameters sought for describing ground movement should be available in the co-earthquake period for the whole Chinese spatial range. As nationwide earthquake monitor network has been established by CEA. It can acquire four elements of data about the earthquake (epicentre location, time, magnitude, focal depth) within several minutes after an earthquake for the whole Chinese territory. Publishing these four earthquake elements is the official job of CEA. Since the data on the four earthquake elements are released

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by a government department (CEA), this guarantees their authoritativeness and availability at any time for comparison with other ground movement parameters. So, we primarily considered selecting them as the earthquake disaster loss calculation factors.

2. Accuracy: although the disaster loss is highly related to the four earthquake elements (especially earthquake magnitude), these elements are too coarse to directly use for loss estimation. The damage caused by two earthquakes of the same magnitude, and even in same earthquake for the four elements can be quite different. For example, the earthquake elapsed time can have a great influence on earthquake damage, and even in one earthquake the damage at different spatial locations is also different. So, in earthquake engineering, seismic intensity is often used to mark the exposure damage. We finally selected this parameter as the disaster calculation factor for earthquake emergency disaster loss assessment. In a real earthquake, the seismic intensity field of influence can be inferred from the four earthquake elements through the earthquake grade-intensity attenuation relationship. We will introduce this in the next section.

4.1.2 Gridding DPM

Building a vulnerability assessment is the foundation for population loss estimation. According to the *Technical Rules for Earthquake Disaster Prediction and Related Information Management* (GB/T19428-2003, 2003), building damage is classified into five categories in China: no damage, slight damage, moderate damage, serious damage and collapse. As Fig. 1 shows and as described above, the building exposure data are classified into four categories according to their structure and anti-seismic characteristics.

In the CEA, the most widely used building vulnerability assessment method is Eq. (1) (Yin, 1995), which is essentially a kind of DPM model:

$$D_{Sj}(I) = P[D_j|I]B_S, \quad (1)$$

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where I is seismic intensity, S is the building type, $P[D_j|I]$ is damage ratio of S type building under I intensity, which is a kind of DPM, and B_S is the total building area of S type building.

The DPM (referring to $P[D_j|I]$) is the key of the estimation. The DPM for this study come from Yin (1995) and is deduced from the hybrid method, which spatially includes the whole Chinese mainland area. In Table 2 we present part of the DPM for the B1-type building as an example to explain its meaning. The earthquake disaster risks of different regions are different, which is represented in the earthquake intensity zoning map of China released by the CEA, shown in Fig. 2. This map depicts the possible maximal seismic intensities that the different regions of China may face in future (based on the possibility of occurrence of no more than 10% in the next fifty years), which represents the actual earthquake disaster risk. When people construct a building in the region with a high possible intensity value, they need to ensure the building has high anti-seismic capacity, which is compulsory according to the Chinese laws. This also means the same type of building in different possible intensity zones will have different anti-seismic abilities. So, the DPM in different possible seismic intensity regions in Table 2 are different.

Generally, seismic intensity represents the damage power and the related destruction caused when the earthquake strikes. According to *China Seismic Intensity Scale* (GB/T 17742-1999, 1999), seismic intensity in China ranges from I to XII. When the seismic intensity at a place caused by an earthquake is less than VI, no damage can be considered to have occurred, and at the upper end of the range, no earthquake of a seismic intensity of XII has been recorded in China. So in this study, the column values of the DPM range from VI to X, as shown in Table 2. Thus, the table values indicates the damage ratio, for example, when a high-rise building with a shear wall structure (B1 type) is struck by an earthquake of seismic intensity VIII and if it is located in possible seismic intensity zone VI, the damage ratio for “no damage” is 40%, but if it is located in possible seismic intensity zone VII, the ratio is 55%.

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The exposure data is in km grid format, as in Fig. 1, so we grid the DPM for the convenience of the loss calculation with the support of GIS.

The gridding of the DMP has two steps: (1) we used an attribute table to store the DPM, then associated the table with the earthquake intensity zoning map of China by “regional intensity”, as shown in Fig. 2; then, (2) we converted the associated intensity zoning map into the grid format, which has same cell size for the exposure data.

4.1.3 Building vulnerability assessment data generation in km grid format

After the gridding operation, the DPM becomes a km grid format layer. Then, Eq. (1) is realized by the map algorithm shown in Fig. 3, the result of which is also in km grid format. So for buildings in a certain intensity, there are spatial multiples of five damage ratios with different types of buildings data and we can obtain four types of building, with five damage degrees (from “no damage” to “collapse”) and five seismic intensity levels (from VI to X), which represents a total of 100 layers.

4.1.4 People loss data generation in km grid format

Many factors are related to deaths in an earthquake, including the building damage, population density, earthquake occurrence time and rescue countermeasures, of which building damage is the key factor (GB/T18208.4, 2005).

A regression model was used in this study, as in Eq. (2) (Ma and Xie, 2000):

$$\log(\text{RD}) = 9.0(\text{RB})^{0.1} - 10.07; \quad \text{ND} = f_t f_p (\text{RD}) P \quad (2)$$

where ND is the number of deaths, RD is people death ratio, RB is the building collapse ratio, P is the total number of people in the calculation area, f_t is the fixed time factor and f_p is the people density fix factor. f_p is determined by Table 3 (Ma and Xie, 2000).

The ratio of people in a building has a great influence on loss of life in an earthquake, which is affected by the time of a day. The f_t value is 1 in the daytime. In the night a dif-

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ferent f_t value is given regarding the different seismic intensities, as shown in Table 4 (Ma and Xie, 2000).

Using the map algorithm method, people loss estimation data were generated in km grid format. It consists of two time periods (daytime and night-time) and five intensity ranges (from VI to X), making a total of 10 layers.

Using this method, we developed a pre-calculated earthquake loss estimation data set in km grid format, using the Python 2.7 and ArcGIS Desktop 10.1 program. The ArcGIS file geodatabase was used to store and manage the loss data, including 100 building damage layers and ten people loss layers. Some of them are shown in Fig. 4.

4.2 Co-earthquake phase

4.2.1 Generating theoretical isoseismal map

The isoseismal map is used to show lines of equal felt seismic intensity, which depict the seismic field of influence of the earthquake. The loss estimation is for emergency response; we used a theoretical isoseismal map as a substitute for the real isoseismal map, which is produced from field investigations several days to several month after an earthquake.

There are two steps in generating the theoretical isoseismal map:

1. Locating the earthquake position and determining the rupture direction of the fault zone causing the earthquake. For this, a Chinese nationwide fault zone distribution map is stored in the ArcGIS geodatabase in which the fault zone direction is recorded. Thus, after an earthquake we can quickly locate the earthquake position on this map and use the nearest fault zone direction as the fault rupture direction of the earthquake.
2. Then, the earthquake grade-intensity attenuation relationship is used to generate isoseismal lines from seismic intensity VI to its maximum theoretical intensity. Spatially, the theoretical earthquake intensity is an ellipse. The length of the long

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axis and short axis of the ellipse should be greater than zero, which controls the maximum intensity. Equation (3) and (4) are the most widely used for establishing the attenuation relationship, fitting east China and west China separately. The east longitude 107.5° is considered to be the dividing line between east China and west China (CEA, 2010).

$$I_\alpha = 6.046 + 1.480M_s - 2.081 \ln(R_\alpha + 25) / I_\beta = 2.617 + 1.435M_s - 1.441 \ln(R_\beta + 7) \quad (3)$$

$$I_\alpha = 5.643 + 1.538M_s - 2.109 \ln(R_\alpha + 25) / I_\beta = 2.941 + 1.303M_s - 1.494 \ln(R_\beta + 7) \quad (4)$$

where I_α , I_β are the average intensity around the ellipse long axis and short axis; R_α , R_β are the short and long axis of the ellipse, the unit is km; and M_s is the earthquake magnitude.

With the support of Eqs. (3) and (4), the theoretic isoseismal map of the earthquake can be quickly generated. Figure 5 shows the example of the Minxian earthquake.

4.2.2 Extraction of statistics on disaster loss

In this stage, the disaster loss calculation essentially becomes a spatial extraction of statistics of pre-calculated disaster loss estimation data, according to spatial distribution of the theoretical isoseismal map. The steps are as follows:

1. First we separately build isoseismal polygons according the seismic intensity value; then these isoseismal polygons are converted into raster (km grid) format, with the intensity value being their attribute value.
2. The grid format isoseismal polygons are separately used to spatially query the pre-calculated grid format loss estimation data from intensity VI to the maximum seismic intensity.
3. The people losses from each queried result are counted.
4. The losses are summed to obtain the final loss for the earthquake.

5 Validation and discussion

5.1 Validation

In order to validate and test the effectiveness of the pre-calculation loss estimation data and corresponding loss estimation method, we selected four actual destructive earthquakes occurring on the Chinese mainland as the experimental cases, which are shown in Fig. 6; the four elements used for the damage loss estimation are displayed in Table 5.

Figure 1 shows the exposure data (building and population) as a dasymetric map in km grid format. In order to compare the administrative unit-based exposure data support loss estimation method, we used the city as the statistics unit and summed up the grid values of the dasymetric map within a city range to generate the administration unit-based exposure data.

The traditional earthquake loss estimation method was used for the test, which includes the following steps: (1) according to the four earthquake elements, a theoretical isoseismal map is generated, (2) according to the spatial distribution of seismic intensity in the isoseismal map, the building damage is separately calculated by the DPM; and (3) the people losses are calculated based on building damage. In this estimation process, the disaster losses are not pre-calculated before the earthquake, and all disaster losses are calculated on the fly.

In the case studies, the building damage estimation and people loss estimation are based on identical calculation formulae, as shown in Eqs. (2) to (4). We had an identical hardware environment for two estimations, which was used to realize the calculation process: Intel Core2 Quad CPU Q9550 @ 2.83 GHz, 4.00 GB RAM, Windows 7 Pro 32-Bit with SP1 in PC. Python 2.7 and ArcGIS Desktop 10.1.

We selected people losses as the estimation aim. There are three reasons for this selection: human losses are more important than building damage losses for earthquake emergency response; human loss estimation appears to be more sophisticated and time-consuming since it is based on building damage loss estimation; and, the real

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people loss value in the actual earthquakes are easy to collect and are confirmed by the government at all levels. So the real human loss values are more authentic and accurate than the building losses in these real earthquakes.

In these case studies, we mainly focused on the evaluation speed and accuracy, but especially speed (for earthquake emergency response and rescue, speed is more important than accuracy), and the results are shown in Table 6.

5.2 Discussion

The experiment shows that the earthquake disaster loss estimation method explored in this study can significantly improve the estimation speed. The disaster estimation can be done within a single minute on a normal personal computer, even when facing a huge earthquake like the Wenchuan earthquake ($M_s = 8.0$). The reason for this speed is the pre-calculation of the disaster loss before the earthquake's occurrence. So after the earthquake, the disaster estimation literally becomes the disaster loss spatial statistics according to the seismic intensity field. The pre-calculated disaster loss method benefits from the dasymetric map approach. Without the support of the km grid format exposure data, it would be hard to perform a meaningful pre-calculated disaster loss estimation. The other benefit of this pre-calculation method is that we can directly estimate loss of lives. However, in the traditional method, it is necessary to go through the building damage estimation on the fly before the people loss estimation.

However, this earthquake disaster estimation method also greatly depends on dasymetric exposure data, which increases the difficulty in the production of the exposure data. Although the dasymetric population data development method and product are increasingly popular and easy to available, it still not easy to obtain appropriate data in many countries and regions, especially in some undeveloped regions. Meanwhile, the building of areal exposure data and corresponding methods are lacking even in developed countries and regions (Han et al., 2013). In this study, we pre-calculated the earthquake losses to improve the estimation speed, but flexibility was also lost in the disaster loss estimation. The updating of the disaster exposure data, calculation

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parameters or calculation formulae will cause the whole pre-calculated disaster loss estimation data to be revised. Furthermore, the pre-calculation disaster loss estimation data will consume some hardware storage: in our study 5.98 GB was used for the storage of these pre-calculated disaster loss estimation data (building damage and population loss in ArcGIS file geodatabase format). With the development of computer hardware, it does not seem a big issue considering the improvement in estimation speed.

The results of the experiment also show that the studied method can improve the accuracy of disaster loss estimation. The reason is the spatial disparity considered in the dasymetric exposure data. Taking population distribution as an example, if just part of an administration unit has been affected by an earthquake disaster, how many population in this unit should be used for loss estimation calculation? The administration unit supported method considers the exposure data averagely distributed inside the census units, as shown in Fig. 7a. However, sometimes this is far from the case; generally people are likely to live around the main settlement points such as the village or city centre (Fig. 7b). Figure 7c displays the dasymetric exposure population data.

The experiment also reveals the results of the estimation of the Minxian earthquake and the Ludian earthquake have large deviations from actual losses. The reason is that the human loss estimation only considers the contributing factor of the building damage. However, in these two earthquakes, people live in the mountainous areas (i.e. 87 % of Ludian County is mountainous). After the earthquakes, serious secondary geological hazards occurred. Many people died as a result of the secondary geological hazards, although the field investigations after the earthquakes do not give the exact numbers of deaths. In the Minxian earthquake, parts of villages were even covered by debris flow.

The pre-calculated km grid-based disaster loss estimation data not only improve the disaster estimation speed and its accuracy; the data also have extra value in emergency earthquake response. We take the Wenchuan earthquake as an example, the earthquake disaster loss estimation result represents not just number of deaths like

the traditional method. It also provides the spatial distribution of possible loss of lives, as Fig. 8 shows. This provides useful guidance to the disaster area emergency rescue actions and for the emergency evacuation of people. Meanwhile, this study gives an applied example of improving earthquake disaster analysis using exposure data in areal format. It has good potential for application in risk analysis and loss estimation for other kinds of disaster.

6 Conclusion

The rapid and accurate estimation of earthquake disaster losses in the period up to 2 h after an earthquake is crucial for earthquake emergency response and rescue (Nie et al., 2012). It is also the key motivation for this study. A new earthquake disaster loss estimation method for earthquake emergency response based on dasymetric exposure data was successfully performed. The method consist of two phases: a pre-earthquake phase and a co-earthquake phase. In the pre-earthquake phase, in four stages, disaster losses have been pre-calculated and stored as a dasymetric map in km grid format, thereby benefiting from the areal format of exposure data. Then, in the co-earthquake phase, the calculation of disaster loss is based on the spatial statistics of the pre-calculated disaster loss estimation data according to the seismic intensity influence field. The core contribution of this study is the development of earthquake disaster loss estimation areal data and a corresponding new two-phase earthquake disaster loss estimation method, which makes it possible to estimate the disaster losses of random earthquakes before or at the point of their occurrence. This improves the speed and accuracy of earthquake disaster estimation for co-earthquake response, and it also serves as an earthquake disaster risk analysis before the earthquake occurrence.

Four recent real earthquakes that have occurred on the Chinese mainland were selected as the experimental cases to validate the new method. The estimation of deaths were separately tested. We conclude that the studied estimation method is effective in improving the speed and accuracy of earthquake loss estimation. The estimation time

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can be reduced to a significantly shorter time, even when faced with a huge earthquake like Wenchuan earthquake using a normal personal computer. Although, the improvement in the accuracy of the studied estimation method is found, deviation between estimated losses and real losses in the Ludian and Minxian earthquakes are found, which cannot be overlooked. This indicates that serious consideration should be given to how the secondary geological disaster impact of earthquakes influences people death estimation, especially for the mountainous areas, which are widespread in south-west China. It is also the most frequent area of earthquake occurrences in China.

The pre-calculation disaster loss estimation data in km grid format also enriches the disaster loss estimation by providing a spatial distribution of possible deaths and building damage. This will be of benefit to earthquake response rescue services and rescue evacuation.

Currently, the pre-calculated earthquake loss estimation areal data and corresponding two-phase loss estimation method are used by the CEA. In future, we will explore the influence of the secondary geological disaster on the estimation of human losses in mountainous areas. The automatic generation of earthquake response countermeasures using earthquake emergency response knowledge (Xu et al., 2014) from estimated earthquake disaster losses is another study direction that we will pursue in the future.

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Table 1. Components and workflow of the two-phase earthquake disaster loss estimation method.

Phase	Stages
Pre-earthquake	Determining earthquake loss calculation factor Gridding damage possible matrixes Building damage calculation People loss calculation
Co-earthquake	Generating theoretical isoseismal map Extraction of statistics on disaster loss

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Table 2. DPM of A type building in a possible VI and VII region (%) (adapted from Yin, 1995).

(a) The DPM in a possible VI region						(b) The DPM in a possible VII region					
I	N	SI	M	Se	C	I	N	SI	M	Se	C
VI	85	15	0	0	0	VI	88	12	0	0	0
VII	60	35	5	0	0	VII	75	23	2	0	0
VIII	40	36	21	2.5	0.5	VIII	55	33	10.3	1.5	0.2
IX	20	0.37	28	12.5	2.5	IX	35	30.5	25.5	7.5	1.5
X	10	15.5	39.5	25.5	9.5	X	15	20.5	40.5	16.5	7.5

Note: I = seismic intensity; N = no damage; SI = slight damage; M = moderate damage; Se = serious damage; C = collapse. We omit the DMP for VIII and IX regions, since they are similar.

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Table 3. Value of f_p .

Population density	$< 50 \text{ km}^{-2}$	$50\text{--}200 \text{ km}^{-2}$	$200\text{--}500 \text{ km}^{-2}$	$> 500 \text{ km}^{-2}$
f_p	0.8	1.0	1.1	1.2



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Table 4. Value of f_t in the night-time.

Intensity	VI	VII	VIII	IX	X
f_t	17	8	4	2	1.5



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Table 5. Basic information on experimental cases.

Case ID	Earthquake name/location	Earthquake time	Magnitude (M_s)	Focal depth (km)
E1	Wenchuan, in Sichuan (31.0° N, 103.4° E)	12 May 2008 14:28	8.0	14
E2	Yiliang, in Yunnan (27.6° N, 104.0° E)	7 Sep 2012 11:19	5.7	14
E3	Minxian, in Gansu (34.5° N, 104.2° E)	22 Jul 2013 07:45	6.6	20
E4	Ludian, in Yunnan (27.1° N, 103.3° E)	3 Aug 2014 16:30	6.5	12

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Table 6. Comparison of calculation of speed and accuracy of experimental cases.

Performance	Estimation method	E1	E2	E3	E4
Time consumed	No grid data support (traditional method)	27 min	7.8 min	8.7 min	8.5 min
	Grid data support (two-phase method)	38 s	26 s	30 s	29 s
People loss estimation accuracy	No grid data support (traditional method)	170 739 (246.7 %)	31 (38.8 %)	68 (71.6 %)	237 (38.4 %)
	Grid data support (two phase method)	63 093 (91.1 %)	75 (93.8 %)	70 (73.7 %)	369 (59.8 %)
Real people loss		69 227	80	95	617

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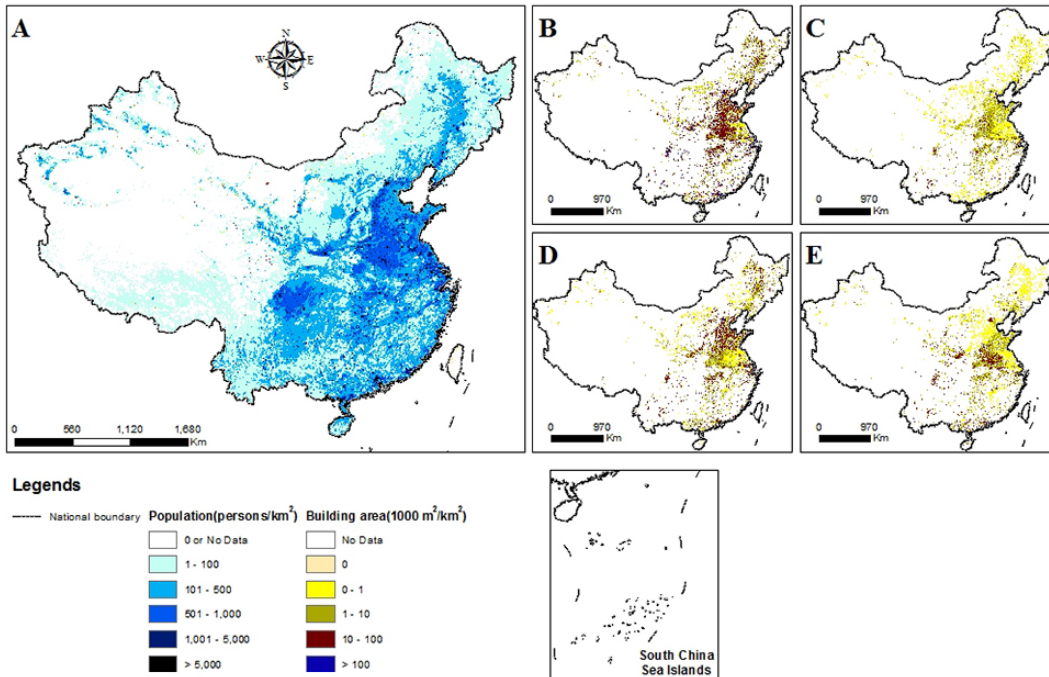


Figure 1. Exposure data in km grid format.

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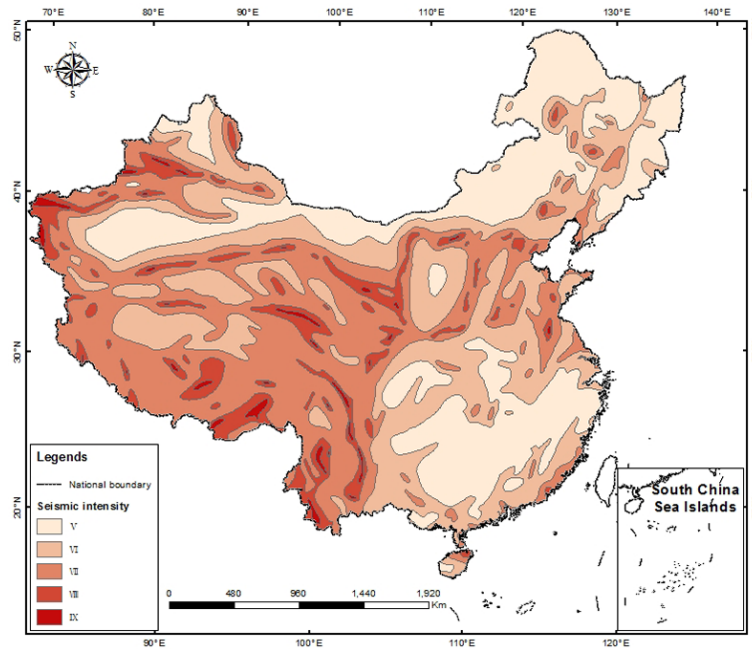


Figure 2. Earthquake intensity zoning map of China (3rd generation).

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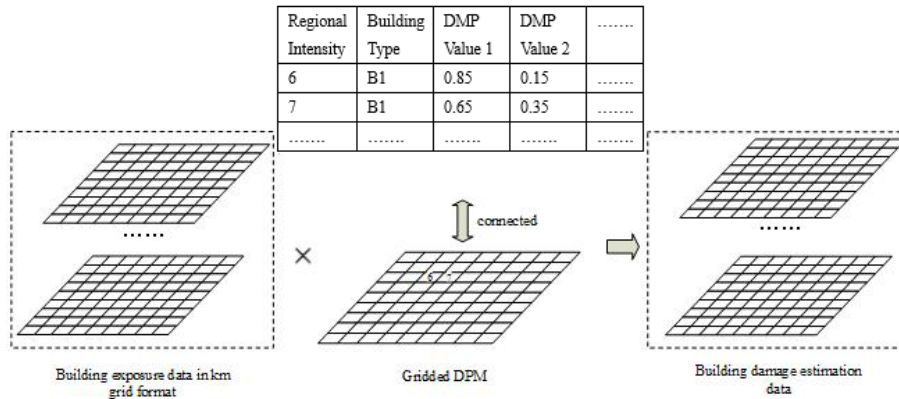


Figure 3. Building vulnerability data calculation process based on map algebra.

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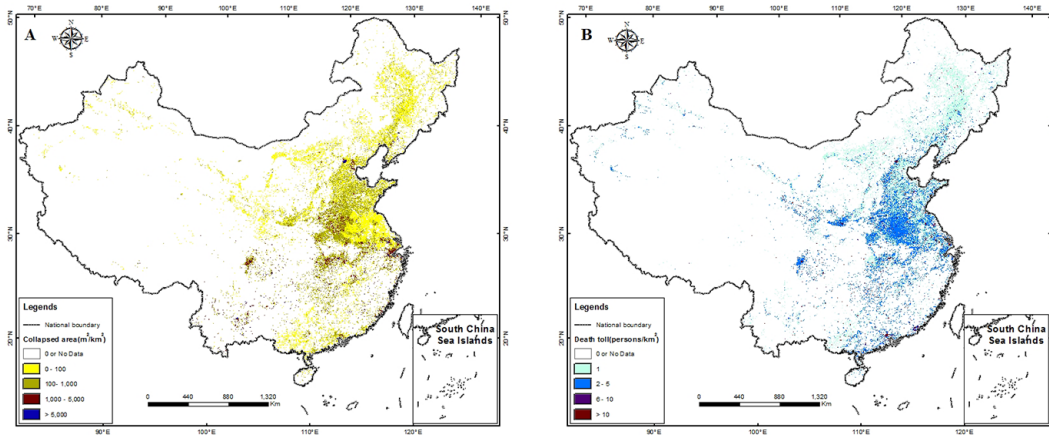


Figure 4. Pre-calculated earthquake loss estimation data set (selected). **(a)** “Collapse” under intensity X of B1 type building; **(b)** people loss under intensity X in daytime.

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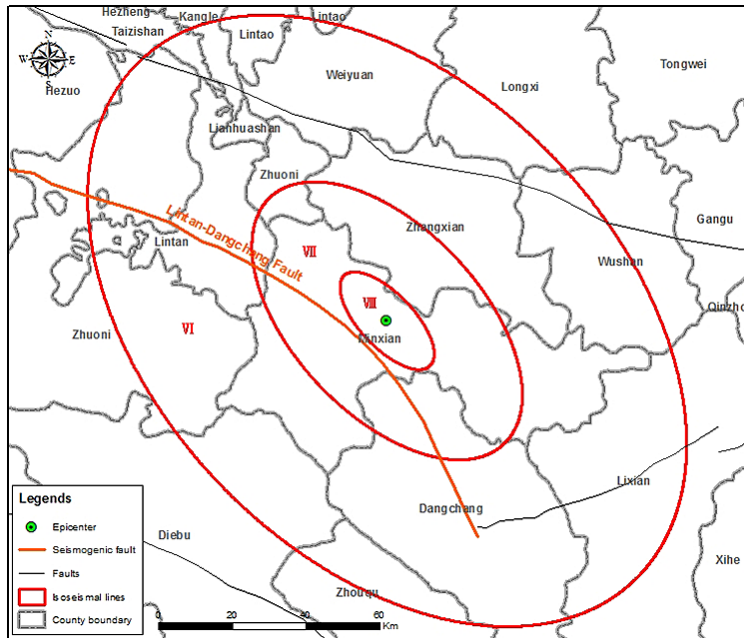


Figure 5. Theoretic isoseismal map of the Minxian earthquake.

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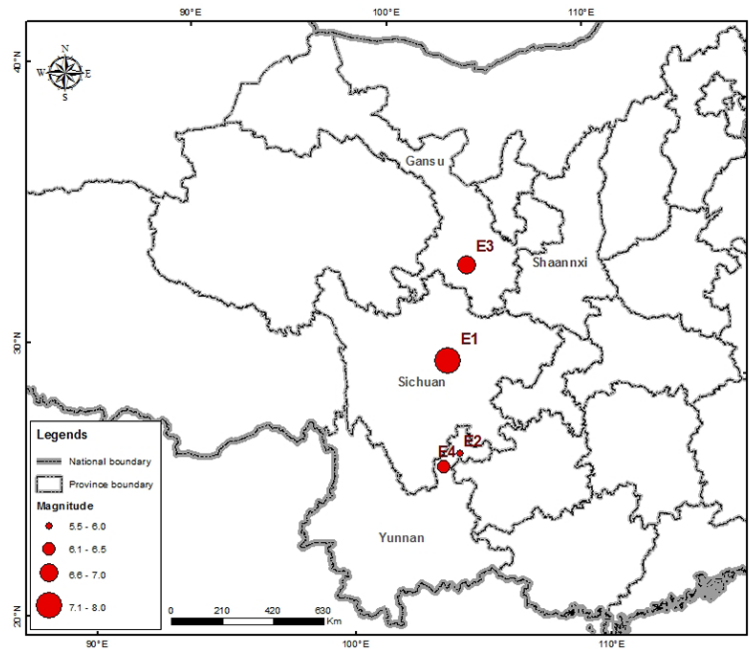


Figure 6. Four real earthquakes used as experimental cases.

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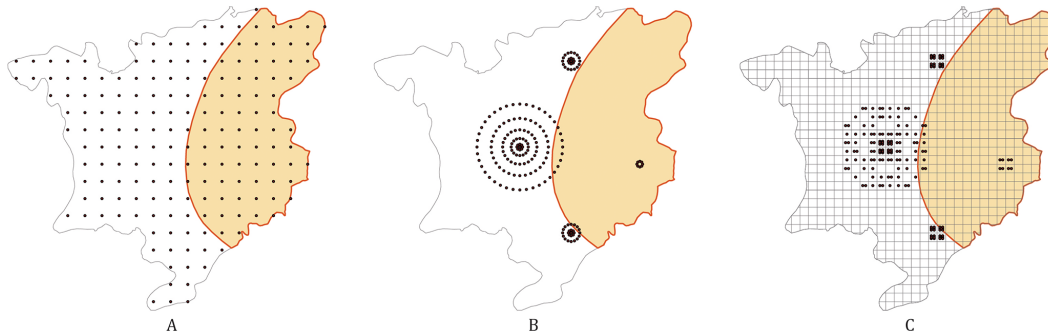


Figure 7. The representation of spatial distribution of population exposure data. The points represent population distribution. The area surrounded by red lines represents the affected disaster area in an administration unit. **(a)** Average distribution inside the whole administration unit; **(b)** actual distribution according to settlements. **(c)** Gridded distribution supported by dasymetric map approach.

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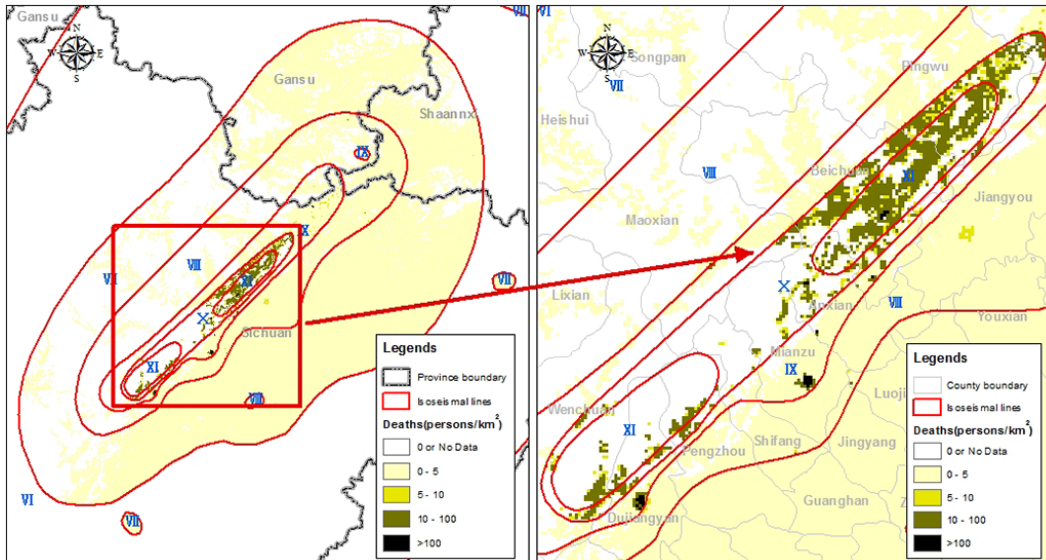


Figure 8. Spatial distribution prediction of possible deaths in the Wenchuan earthquake.

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