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THE DISTRIBUTION OF SEISMIC CAPACITY OF BUILDINGS IN MAINLAND CHINA

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ABSTRACT

Building damage is the major factor causing economic loss and casualties in earthquakes. Macroscopically mastering the overall seismic capacity of buildings in different regions of China provides a scientific basis for guiding local or regional construction planning before earthquakes. This research was performed as follows: firstly, the construction characteristics, load bearing system, and uses of several thousands of sample buildings from more than 400 survey areas in 26 provinces of mainland China were analysed to obtain the key factors influencing the seismic capability of the buildings in mainland China; secondly, this work categorised mainland China into 12 types of areas according to their different seismic capacity so as to reveal the difference between seismic capacities among the different building structures in each of the research areas; thirdly, based on analysed results of the vulnerability of buildings with different structures in dozens of cities in the most recent two decades in the prediction of seismic damage, the seismic vulnerability matrices of these different building structures in different regions was classified based on the 12 types of seismic capacity was obtained; lastly, by considering average seismic damage index for each type of building in 1 km × 1 km grids across the different areas with their varying seismic intensities, the seismic capacity indices of structures across mainland China were calculated. Using ArcGIS software, the distribution of seismic capacity for buildings in mainland China was drawn.

Keywords: Buildings; seismic capacity; Comprehensive division and classification; vulnerability; ArcGIS

1 INTRODUCTION

Statistics show that China's earthquakes account for 35% of all continental earthquakes exceeding Ms 7.0. In China an Ms 7.5 earthquake occurred every five years on average, while an Ms 8.0 earthquake happens every 10 years, which means that one third of China's land area is subject to significant seismic risk. Since the 1900s China has been one of few countries to have suffered the most serious seismic damage: casualties in China resulting from earthquakes have surpassed 50% of the world total. In particular, destructive earthquakes have happened successively in recent years leading to huge economic loss and many casualties.

The destructive Wenchuan earthquake occurred in Sichuan Province on 12 May, 2008, and caused 69,227 deaths, 17,923 missing persons, and 374,643 injuries, as well as a direct economic loss of 845.1 billion yuan. Moreover, this serious hazard struck an area of more than 400,000 km^2, 23.143 million buildings were damaged, among which, 6.525 million buildings collapsed (Sun et al. 2010). The Ms 7.1 Yushu earthquake resulted in 2,968 deaths and 12,135 injuries, additionally, a large

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number of residential buildings collapsed and serious destruction occurred to public facilities including schools and hospitals (Chen et al. 2011). The Lushan earthquake led to 196 deaths, 21 missing persons, and 11,470 injuries, while the direct economic loss induced by building damage and collapse is estimated to be 17.611 billion yuan (Li et al. 2013). The Ms 6.5 Ludian earthquake in 2014 caused 617 deaths, 112 missing persons, and 3,143 injuries, with an economic loss of approximately 20 billion yuan (Hou et al. 2015).

Experience, both national and international, has shown that the casualties and economic loss induced by earthquakes are mainly attributed to the destruction and collapse of buildings. According to available statistical data, 95% of all casualties in earthquakes were caused by the destruction of buildings. Macroscopically mastering the distribution and the level of seismic capacities of buildings in China is of great importance. It plays an essential role in government-directed construction planning, seismic strengthening of buildings, and in enhancing public awareness of disaster prevention before the occurrence of an earthquake. Besides it can guide earthquake emergency responses, loss assessment, and so on, during and after, an earthquake.

Firstly, the identification of earthquake disaster risk is regarded as a premise for carrying out seismic disaster prevention and mitigation, namely, distinguishing the seismic capacity of the buildings in different regions. The seismic capacity for each of regions was investigated as follows: 1) mainland China was divided into grids (1 km × 1 km); 2) based on the division and classification methods of seismic capacity, the contributions of the parameters involving seismic fortification, GDP, administrative divisions, land-use types (township or rural), the population density, and the year of construction of the buildings in the research region were analysed to divide the seismic capacities of the buildings into 12 types in each grid square; 3) obtaining vulnerability matrices for each type of building in a region with a 1 to 12 rating of their seismic capacity; and 4) a comprehensive seismic damage index is calculated by multiplying the average seismic damage index by the areas of building, which was used for evaluating the seismic capacity of the corresponding region.

2 A COMPREHENSIVE CLASSIFICATION

2.1 The difference between building structural characteristics

China is a vast land with different types of buildings structures, Yin Zhiqian classified building structural characteristics into 21 categories and 168 sub-classes (Yin et al. 1996). The primary reasons leading to the differences mainly include: regional and environmental differences: due to the restriction of climate conditions, masonry buildings constructed in South China have walls with a thickness of 18 to 24 cm with light-weight, double-pitched roofs; however in Northern China, the masonry buildings have wall thicknesses of 37 to 49 cm with flat, heavy-weight, roofs; cultural differences: rubble mound structures, stilt buildings of Kejiazu Nationality and column-and-tie construction are dominant forms in the Midwest and Southwest of China, and reinforced soil walls and single-layer brick-concrete structural walls are primary types of structures used in Northwest and Northeast China; differences in construction era: China's seismic code started from *the Draft of National Building Code in Earthquake-struck Areas* (unpromulgated) in 1959, until now it has covered 60 years use. The buildings built in different times exhibit diverse seismic capacities with the changes in seismic fortification levels, construction materials and structural requirements; differences in administrative supervision: the buildings in urban China are usually uniformly planned by government, and are supervised during construction. Most buildings aim to satisfy norms governing local fortification and construction standards, but houses in rural areas are mainly built by farmers themselves. The seismic structural requirements are considered only occasionally, so most houses in rural areas fail to meet the seismic fortification standards; and the differences in population density

2.2 The diversity of building structures

Until the 1970s, different buildings structures appeared in different areas of China: the brick-concrete-structure is mostly commonly seen in townships of China. In rural Southwest China, the rubble mound structure, stilt buildings, and column-and-tie construction are the dominant structural forms. Raw-soil structure and brick-wood structure are dominant types in the rural areas of Northern China and in Southeast China, respectively. An Ms 7.8 earthquake hit Tanshan city on 28 July, 1976: the entire urban region was subjected to Ⅺ-degree intensity. Since the city was unfortified, all buildings and houses were destroyed or collapsed, causing more than 240,000 deaths. Gradually, building structural forms have changed in townships: brick-concrete-structured buildings in China's large and medium-sized cities have been replaced by a large number of reinforced concrete structures and steel structures. The reinforced concrete shear-wall has been popularised in residential buildings and the large-span spatial steel structure has become the preferred option when constructing stadia and business centres. Reinforced concrete buildings are the most common type found in urban areas. The proportion of reinforced concrete structures in medium-sized cities and rural area is rapidly increasing: at the same time, an increase in the number of fortified masonry buildings and brick-wood buildings is found in rural areas. The casualties resulting from the Ms 8.0 earthquake in Wenchuan, Sichuan Province, on 12 May, 2008, was far fewer than those in the Tangshan earthquake owing to the earthquake struck-areas in Wenchuan being in the range of Ⅶ-degree fortification and a majority of the township's buildings presented a certain seismic capability even though the buildings or houses in township and rural areas had not lived up to seismic fortification standards, this indicates that a large number of novel structural buildings with seismic capacity had been built in township and rural areas under people-oriented governance philosophies adopted by the Chinese Government.

In the next section of this paper, buildings structures are classified into different types as follows: (1) high-rise structures; (2) multi-storey reinforced concrete structures; (3) masonry structures; (4) brick-wood structures; and (5) other structures such as soil-reinforced structures, stone structures, and cave houses.

2.3 Factors influencing the seismic capacity of buildings

Seismic capacity represents the ability to withstand seismic disasters of buildings when earthquake happens. Vulnerability means all the possible losses of the hazard-affected bodies facing seismic disasters and the ability to cope and adapt it. In the current investigation, the structural characteristics and seismic capacity of several thousands of buildings from more than 400 survey areas in 26 provinces of China were surveyed. The survey areas cover urban, suburb, township, and rural areas in provincial cities, large and medium sized cities and other general cities. The surveying areas were chosen considering developed areas, underdeveloped areas, and minority residential areas: their distribution is shown in Figure 1. The sample classification and survey were conducted based on dominant types of building structures. In this work the survey ranges include single-storey, multi-storey, and high-rise building structures for residential, official, and business use built in the period in, or before, the 1980s as well as newly-built structures from the 21st century. The building structures were divided into five types: 1) high-rise structures; 2) multi-storey reinforced concrete structures; 3) masonry structures; 4) brick-wood structures; and 5) other structures.

By analysing the construction characteristics, load bearing system, and uses of several thousands of sample buildings from more than 400 survey areas, it was found that the seismic capacities of buildings in China are closely influenced by following factors: (1) administration: as the county-level areas and the areas above county-level are strictly regulated by local government, constructed buildings generally conform to seismic capacity requirements in these regions, however some townships, and the majority of rural areas, are found to have a great many of unfortified and self-built buildings or buildings constructed without supervision by local government. Although some buildings adopted seismic measures, they remain far from meeting prevailing seismic requirements; (2) population and economic development: statistics show that, in more developed areas with greater population densities, people are likely to more focus on seismic capacity: there are more high-rise buildings, multi-storey reinforced concrete structures, and masonry structures with properly designed seismic fortification, meanwhile most of the buildings in these areas were built to a systematic seismic design code, and favourable construction quality, however in underdeveloped areas with small population densities, most buildings were designed and built without strictly following formal seismic criteria due to the absence of strict supervision by government. Moreover, there are many self-built, unfortified, buildings, so their seismic quality cannot be guaranteed; (3) seismic fortification levels: China has enacted seven stipulations and revisions of her seismic design code since 1959. Each of the revisions plays a significant role in promoting the development of seismic design for buildings in China, representing that seismic design levels of buildings in China are constantly improving. Our survey results show that buildings designed in consideration of seismic effects exhibit a greatly different seismic capability compared to those without cognisance of seismicity. Buildings designed with seismic fortification, or seismic strengthening, outperformed unfortified buildings; meanwhile, buildings constructed according to the new seismic standard design code were superior to those constructed on the basis of previous seismic standard design codes in terms of seismic capacity. Additionally, the seismic capacity of the buildings in the areas with high seismic fortification levels were greater than those with lower seismic fortification level; (4) land-use type: The Institute of Geographic Sciences and Natural Resources Research of The Chinese Academy of Sciences (CAS) established a database of land-use status across mainland China at 1:100,000 scale, in which, residential use includes residential use in rural areas and other construction use, which ranges from land uses in large, and medium-sized cities, counties, townships, and rural areas. The survey results indicate the seismic capacity of buildings constructed under strict supervision of local government in planned construction projects in townships meet the requirements; however in unplanned construction works, self-built projects account for the majority built, with weaker seismic capacity as a result.

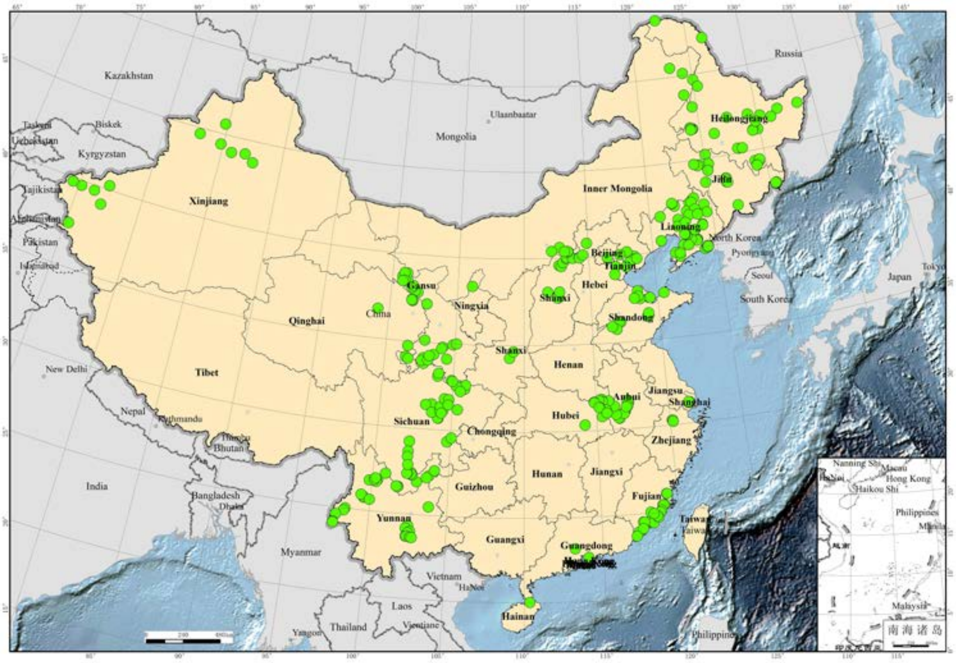


Figure 1 The distributions of the buildings in China

2.4 Comprehensive classification of the seismic capacity of the buildings in different regions

The seismic capacity of the buildings for each region is associated with all individual buildings, therefore the seismic capacity integrating all individual buildings can reflect overall seismic capacity of a region: however it is hard to calculate the seismic capacities of millions, or tens of millions, of buildings. The idea of this study is to analyse the seismic capacity given the sample analysis base on the datasets of *in situ* survey data as follows: at first, mainland China was divided into grids (1 km × 1 km), and the seismic capacities of each grid square were classified into 12 levels. Then the levels of seismic capacity for each grid were calculated based on five indices including population density and economic development, by doing so, the comprehensive seismic capacity in a given region can be obtained. Furthermore, the vulnerability to seismic damage prediction was compared with that of buildings damaged by actual earthquakes, then the distribution of seismic capacity across mainland

China can be obtained by a weighted averaging process.

(1) Mathematical model

To assess the seismic capacity of the buildings in 1 km × 1 km grid, the comprehensive influence factor of seismic capacity for the buildings is labelled as CIF_d and the effect factors of seismic capacity are H_{di}. The data sources of each factor are: (1) Chinese population data; (2) GDP data; (3) basic seismic fortification intensity data; (4) Land-use planning data; and (5) admininstrative data. The contributions of each influence factor to seismic capacity are denoted by the weight r_i and are calculated thus:

$$CIF_d = \sum_{i=1}^{n} r_i H_{di} \tag{1}$$

Where $\sum_{i=1}^{n} r_i = 1$.

（2）The calculation of two influence coefficients: population and GDP

Firstly, a research region was divided into provincial districts, prefecture-level cities, townships, and rural areas according to administrative divisions. By taking provincial districts as benchmark data, raw data were transformed into a set of comparable data series using the average-value method: namely, the average value V_{mav} of GDP or population of all grid data of all provincial districts in the research area was first derived, then, the data in each 1 km × 1 km gridded region in the research area were divided by V_{mav} respectively so as to acquire a new dimensionless data series, which is used as a influence coefficient H_{di}, where values of H_{di} greater than 1 were set to 1 and thus:

$$V_{mav} = \frac{1}{n}\sum_{k=1}^{n} v_{mn} \tag{2}$$

$$H_{di} = \frac{v_n}{V_{mav}} \tag{3}$$

Where, V_{mav} is the average value of the gridded data in the provincial districts of the research area, v_{mn} represents the data in each 1 km × 1 km gridded provincial districts in the research areas, H_{di} refers to the coefficients of the different influencing factors in the research area, and v_n denotes data from each 1 km × 1 km grid.

(3) Calculation of two influence coefficients: land-use and degree of seismic fortification

The influence coefficient for land-use is calculated based on the data for construction land (urban and non-urban). The seismic fortification was classified into five grades: unfortified, Ⅵ-degree fortification, Ⅶ-degree fortification, Ⅷ−degree fortification, and Ⅸ−degree fortification. The seismic fortification intensity coefficients were obtained from a statistical analysis of historical seismic damage data and the local fortification conditions in the research area (Table 1).

Table 1. Coefficients considering seismic fortification intensity.

Fortification condition	**Unfortified**	**Ⅵ**	**Ⅶ**	**≥ Ⅷ**
Coefficient	0	0.5	0.8	1

(4) The value of weights

By analysing the influences of population, GDP, land-use, and fortification intensity on the seismic damage to buildings, it is found the fortification intensity exerts the greatest influence on the seismic capacities of buildings in different regions, followed by GDP, while population has the smallest influence. Besides, the influence of administrative divisions on the structural seismic capacity was also explored. To determine the weights of varying influence factors, this study used an analytical hierarchy process (AHP) to quantify the effects of different influence factors on the seismic capacity.
The analysis and calculation based on AHP consisted of three steps: 1) Establish a hierarchical structural model; 2) Construct a judgment matrix; and 3) Perform a consistency check. The weights of the matrix that passed the consistency check are calculated using a geometric mean method as follows:

$$r_i = \frac{(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}, \qquad i = 1, 2, \cdots, n \tag{4}$$

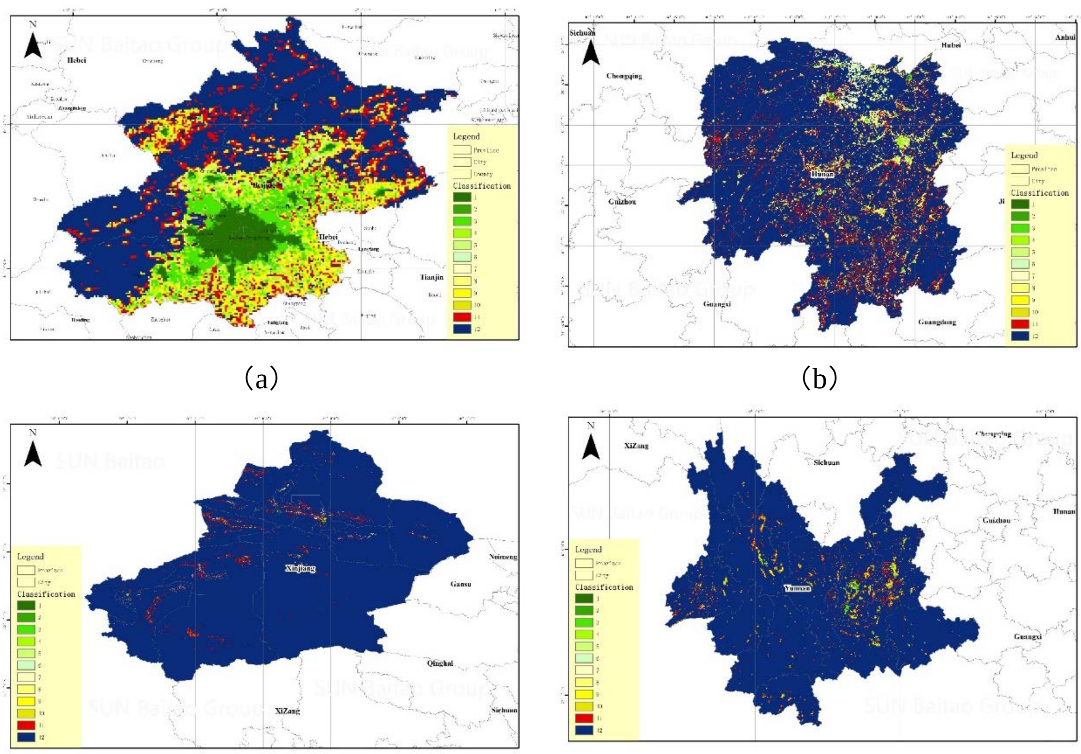
Where r_i denotes the weight vector of the matrix;
a_{ij} refers to the elements in the i^{th} row and the j^{th} column;
n is the order of the matrix.

Using Eq. (4), the weights of different influence factors are calculated using a geometric mean method (Table 2).

Table 2. Values of weight coefficients.

Factor	**Population**	**GDP**	**Urban construction land**	**Fortification intensity**
Weight	0.07	0.26	0.11	0.56

The influence factors were adjusted using aforementioned method of division and classification. Consequently, mainland China was divided into 12 classes of regions according to the seismic capacity of their buildings (Sun et al. 2017). Figure 2 shows this for four provinces of China.



（c）　　　　　　　　　　　　　　　　　　　　　　（d）

Figure 2 Comprehensive division and classification for seismic capacity of buildings in four provinces of China: （a）Comprehensive division and classification in Beijing City; （b）Comprehensive division and classification in Hunan Province; （c）Comprehensive division and classification in Xinjiang Province; （d）Comprehensive division and classification in Yunnan Province

3 ANALYSIS OF SEISMIC VULNERABILITY OF BUILDINGS

To evaluate the seismic capacity of the buildings in different regions, this research aims to use the method integrating the survey and forecasts of seismic damage to build a seismic vulnerability matrix aiming at different structural types of buildings in different regions.

(1) Classification of structural type

As the seismic vulnerability matrix was proposed on the basis of the different structural types, it was necessary to carry out classification of building structures in different areas. This study categorised the buildings structures in mainland China into five types through many seismic damage surveys, *in situ* investigations of buildings struck by earthquake, and use of Technical Code for Prediction of Seismic Damage and Information Management Systems (GB/T9428, 2014). The five structural types are: high-rise buildings, multi-storey structures, multi-storey framed structures, masonry structures, brick-wood structures, and other structures.

(2) The analysis of seismic damage information

Historical seismic damage data are first-hand data used by researchers when analysing the trends in earthquake occurrences and engineering structural failures. These data usually involve important information containing the time, locations, and intensities of earthquake events, the degree of building structural damage, the number of damaged buildings, economic losses, and casualties. On this basis the authors collected the data from *The Report of Estimated Seismic Damage in Mainland China* (CEA et al. 1996; CEA, 2001; CEA, 2010) and information about disastrous seismic damage occurring in recent years. The damage status of those buildings struck by an earthquake was summarised. Moreover based on the estimated results of the buildings in the report, we sorted the damage ratios for the five damage degrees of each structural type and then, we further established the seismic damage matrix for various types of buildings subjected to different seismic intensities in earthquake-struck regions. Furthermore, using an improved empirical seismic damage matrix (Hu et al. 2007), the incomplete seismic damage matrix was improved.

(3) Forecasting seismic damage

By summarising seismic damage data, it is found that the majority of disastrous earthquakes in mainland China occurred in provinces such as Yunnan, Gansu, Xinjiang, Sichuan, and Tibet: however, there is a lack of data pertaining to disastrous seismic damage information in North China, South China, and Northeast China, and buildings in most cities have not been struck by large magnitude earthquake events. To understand the seismic capacities of structures/buildings and infrastructure, and the potential damage thereto in possible future earthquakes, China has successively carried out predictions of seismic damage and estimates of earthquake-induced loss since the Seventh Five-Year Plan (1986-1990). In this research, the forecast seismic damage data for 20 cities including Jinjiang, Shishi, Fuzhou, Taiyuan, Dongying, Taian, and Daqing were collected so as to form the seismic vulnerability matrix for building structures.

(4) Seismic damage to grouped buildings

The seismic damage data can reflect the seismic vulnerability of building structures in some cities; however they fail to represent the status with regards seismic capacity for buildings in all regions across mainland China. Hence, this research simulated the seismic capacity of buildings in cities which have never suffered an earthquake and thus show no seismic damage, using newly-developed methods to predict the seismic damage to groups of buildings.

The commonly used predictive methods for estimating seismic damage to a group of buildings include: empirical statistical methods, semi-empirical theoretical methods, intelligent agent-assisted decision approaches for forecasting seismic damage, *etc*. The literature search revealed a predicative method for estimating the seismic damage to a group of buildings based on an existing seismic damage matrix in 2005 （Sun et al. 2005）. This method sufficiently utilised sample data pertaining to existing seismic damage and forecast seismic damage to compare with the status of buildings in predicted areas. As a result, they simulated the seismic vulnerability of the buildings in various regions. Furthermore, the authors improved this method by proposing an approach to forecasting seismic damage based on the level of seismic fortification thereof (Zhang, 2010). This method obtained the seismic damage matrix using data about previous seismic damage and seismic damage predictions in cities to distinguish between seismically fortified buildings and unfortified buildings. In this work, we predicted the seismic vulnerability of groups of buildings in different regions by using the aforementioned predictive tools.

4 THE SEISMIC CAPACITY INDEX OF A BUILDING

4.1 Mathematical model

The overall seismic capacity of the buildings in a region is associated with the distribution, and structural types, of the buildings in the region in addition to being influenced by the seismic capacity of the buildings themselves. On the basis of comprehensive administrative divisions and classifications, we calculated the seismic vulnerability of different types of buildings in different regions to find an average seismic damage index for various buildings under different seismic intensity events. By considering the seismic vulnerability under the influences of different structural types, construction areas, and different seismic intensities, the mathematical model for the distribution of the seismic capacities of the buildings based on 1 km × 1 km gridded data was built:

$$E_i = \frac{\sum_{j=1}^{n} C_{ij} A_j}{\sum_{j=1}^{n} A_j} \tag{5}$$

Where, E_i represents the distribution of the seismic capacities for the buildings based on the 1 km × 1 km gridded data under a degree of seismic intensity *I*;
Where C_{ij} is the average seismic damage index of the *j*th structural type of building under an event with a degree of seismic intensity *I*; A_j refers to the total construction area occupied by the *j*th structural type of building.

The seismic damage index proposed by earthquake engineering experts led by Liu Huixian *et al*. aims to quantify structural failures: namely, the level of seismic damage suffered by building structures was quantified, and the values lay within the range [0, 1] which were then used to indicate the degree of seismic damage suffered by a given building structure (Table 3).

Table 3. The relationship between seismic damage indices and degree of seismic damage.

Level of damage	**Basically intact**	**Slight damage**	**Moderate damage**	**Severe damage**	**Collapse**
Seismic damage Median	0	0.2	0.4	0.7	1.0

Seismic damage Limits	[0, 0.1]	(0.1, 0.3]	(0.3, 0.55]	(0.55, 0.85]	(0.85, 1.0]

The average seismic damage index denotes the average seismic damage degree of some types of buildings under a specific seismic intensity event in a given region or city, *i.e.*, the average seismic damage index of the mean of the seismic damage indices or average seismic damage index of a group of buildings, and is calculated thus:

$$C_{ij} = \sum_{j=1}^{5} D_j \times P(D_p \mid I) \tag{6}$$

Where, C_{ij} is the standardised seismic damage index of a certain type of building under an event of seismic intensity *i*; D_j is the median seismic damage suffered by the building structure under an event of seismic intensity *j*; and $P(D_p \mid I)$ represents the probability that type of damage *p* occurs to structural type of building *x* under an event of seismic intensity *i*.

4.2 The distribution of seismic capacity

Using GIS mapping software, this study calculated the distribution of seismic capacity of buildings in China under different seismic intensities. Fig. 4 shows the distributions of the seismic capacities of buildings in Beijing, Hunan, Xinjiang, and Yunnan Provinces.

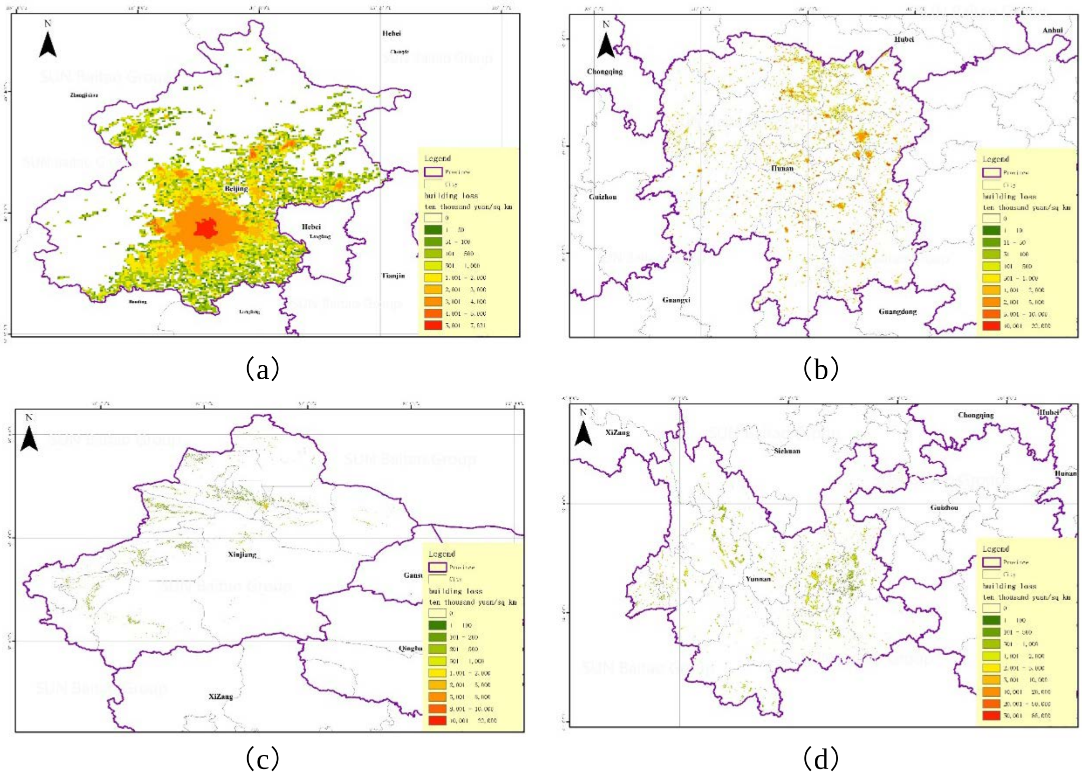


Figure 3 Distribution of seismic disaster risk loss of buildings in earthquakes with seismic basic fortification intensity in four provinces of China: （a）Distribution in Beijing City; （b）Distribution in Hunan Province; （c）Distribution in Xinjiang Province; （d）Distribution in Yunnan Province

5 CONCLUSION

The analysis of the distribution of seismic capacity for buildings in mainland China was undertaken to establish a systematic research method for future use. Furthermore, using ArcGIS software, the distribution of seismic capacity of buildings under different seismic intensities in some provinces of mainland China was drawn. The following conclusions were drawn:

1) The seismic capacity of buildings is not only influenced by the buildings themselves, but also by multiple factors including administrative divisions to regional public administration, seismic fortification, population, and economic development. In this work, the seismic capacities of buildings in mainland China were classified into 12 levels by analysing these key factors in mainland China.

2) The seismic vulnerability matrix of buildings is seen as a comprehensive index for measuring the seismic capacity of a certain type of building in a city or a region. This research makes full use of existing information to construct the seismic vulnerability matrix for different types of buildings in various regions in China, including existing seismic damage, seismic forecasts, and mature seismic damage prediction approaches for groups of buildings.

3) Considering the average seismic damage indices, and the distribution of construction areas for different types of buildings, a mathematical model for predicting the comprehensive seismic capacity index of buildings is proposed based on a 1 km^2 grid. Then, the distribution map of the seismic capacity of buildings subjected to different earthquake magnitudes was simulated: this presents the seismic capacity of the buildings in various regions macroscopically and provides a basis from which the Chinese Government can make decisions relating to construction planning.

6 ACKNOWLEDGEMENTS

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