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Distribution of seismic capacities and seismic disaster risk of buildings across China

GX. Zhang[1], BT. Sun[2]

[1] *Associate professor, Institute of Engineering Mechanics, China Earthquake Administration, zgx@iem.cn*
[2] *Director/professor, Institute of Engineering Mechanics, China Earthquake Administration, sunbt@iem.cn*

Abstract

At present, seismic disasters in China are complicated and changeable and destructive earthquakes occur frequently. With faster socio-economic development, the seismic disaster risk keeps rising. Vulnerability of buildings in seismic disasters is a core issue that restricts urban sustainable development during the current course of China's urbanisation. Engineering structures are the primary hazard-affected bodies in earthquakes. Damage to buildings is one of the main factors causing economic losses and causalities during earthquakes. Therefore, it is necessary to evaluate seismic disaster risk of buildings in different regions, infer actual seismic capacities and distribution of existing buildings, thus comprehensively mastering the current seismic capacity of buildings in a city or a region, and reveal the distribution of differences in seismic capacities of buildings in different regions. These are beneficial for the government to accomplish earthquake prevention and disaster mitigation planning and take targeted measures such as reinforcement, reconstruction, and emergency preparedness before earthquakes, timeously mastering disaster situations and commanding emergency response units during earthquakes, and evaluate losses thereafter. The research involved the following aspects: 1) The construction features, loading bearing system, and utilisation of thousands of building samples at more than 400 research sites in 26 provinces in China were summarised and analysed, to determine main factors that influence seismic capacities of buildings in China; 2) The relationships between factors including population density, gross domestic product (GDP), land-use type, and seismic fortification in different regions with seismic capacities of all kinds of buildings therein were analysed. On this basis, the Chinese mainland was classified into 12 types of regions, in each of which the differences in seismic capacities of different types of buildings were elaborated; 3) The vulnerability of all types of building structures in different regions subjected to more than ten destructive earthquakes on the Chinese mainland was summarised. Meanwhile, the vulnerability matrices of all types of building structures in the 12 types of regions were obtained by performing simulation using the results of vulnerability analysis of all types of structures in the seismic disaster prediction of tens of cities in most recent 20 years; 4) Considering areas of all types of buildings in 1 km × 1 km grids and the average seismic damage index of corresponding types of structures under different seismic intensities, the seismic capacity indices of building structures in the whole country under different seismic intensities were calculated. By using ArcGIS software, the distribution of seismic capacities of buildings in the Chinese mainland was mapped.

Keywords: building; seismic capacity; comprehensive division and classification; vulnerability; ArcGIS

1. Introduction

Experience of earthquake damage across the world has made it clear that the loss of life and property due to earthquakes is mainly caused directly by damage and collapse of buildings. According to statistics, 95% of all causalities caused by earthquakes are the result of damage to buildings. Therefore, mastering the seismic capacities of buildings in China is an effective means of mitigating seismic disasters. This is because it enables government and the public to learn of the distribution of seismic capacities of local buildings, make targeted planning and reconstruction in weak areas before earthquakes, and learn of the extent of damage in different regions timeously during earthquakes, so as to take effective measures against further damage.

At first, recognition of possible disasters in a region, that is, distinguishing differences in seismic capacities of building structures in different regions is the premise to prevent and mitigate disasters. The present research investigated the seismic capacities of buildings in each region using the following steps: ① taking 30″ × 30″ grids as the computing unit; ② building a division and classification model for seismic capacities of buildings in a region by analysing relationships between seismic fortification level, economic development level (indicated by gross domestic product (GDP)), administrative division, land-use type (urban or rural), and population density of the region with seismic capacities of buildings; ③ constructing vulnerability matrices of different types of building structures in various regions by analysing seismic vulnerability of each type of structure in different regions; ④ proposing an analysis method for seismic capacities of buildings in different regions by considering differences in stock and seismic capacities of all types of buildings in each region, so as to evaluate the overall seismic capacity of buildings therein.

2. Comprehensive division and classification for seismic capacities of regional buildings

2.1 Differences in structural and construction features

Diverse types of building structures are constructed across the vast area of China. Yin Zhiqian [1] classified existing building structures in China into 21 classes and 168 sub-classes. The presence of so many types of structures in China is mainly because: 1) Regional and environmental differences. Limited by climatic conditions and for heat preservation and rain-proof purpose, masonry buildings in south China are mainly built with walls 18~24 cm thick and light-weight double-pitched roofs; In comparison, walls of masonry buildings in north China are generally 37~49 cm thick, and heavy-weight flat roofs are commonly used. 2) Cultural differences. Rubble mound structures, stilt buildings of Kejia nationality, and column-and-tie timber constructions are widely distributed in the central and western regions and residential areas of Tibetan and Qiang nationalities; while buildings in north-western and north-eastern regions are dominated by structures with reinforced soil walls and single-layer brick-concrete structures. 3) Differences in construction era. The seismic code has been used for nearly 60 years in China, from 1959 with the Draft of National Building Code in Earthquake-Struck Areas (not issued) to 2016 when the Code for Seismic Design of Buildings (GB50011-2010) was partially revised. Buildings constructed in different eras have different seismic capacities with the changes in seismic fortification levels, construction materials, and construction requirements. 4) Differences in administrative supervision. Buildings constructed in urban areas are mainly uniformly planned by and under supervision of the government during construction. A majority of these buildings aim at meeting local fortification and construction standards. Buildings in rural areas are generally constructed by farmers themselves, with seismic requirements considered occasionally, while most buildings do not meet current fortification standards. 5) Differences in population density.

2.2 Factors influencing the seismic capacities of buildings

The present research investigated and collected basic conditions, construction features, and seismic capacities of thousands of buildings from 400 research sites across 26 provinces of China. The research sites included urban areas in provincial capitals, large and medium-sized cities, and other cities, as well as suburbs, counties, townships, and rural areas, in economically developed and backward areas, and minority residential areas. Through analysis, it was found that the seismic capacities of buildings in China are closely related to the following influencing factors: 1) administrative division: buildings constructed in areas at county-level and above exhibit seismic capacities according to their fortification intensity due to strict regulation by Local Government; while in some townships and most rural areas, there are numerous self-built unfortified buildings allowed as a result of weak supervision. Even though some buildings were constructed with seismic measures in mind, they are still far from satisfying general seismic requirements; 2) Population and economic development: according to statistics, people in more developed areas with a larger population density have higher awareness of the need for seismic protection. These areas are found to have more high-rise buildings, multi-storey framed structures, and fortified masonry structures. Moreover, a majority of these buildings conform to the normal seismic design code and are constructed to a high standard. In comparison, because of the lack of strict supervision by local government, many buildings in underdeveloped areas with a small population density were designed and constructed without conforming to formal seismic criteria (there are many self-built structures completed without seismic measures, the seismic performance of which cannot be guaranteed); 3) seismic fortification levels: the investigation has shown that buildings designed with and without seismic fortification have greatly differing performances when subject to seismic action: fortified or reinforced buildings show better performance than those that are unfortified. Moreover, buildings constructed following new seismic design codes have higher seismic capacities than those built according to previous codes. Furthermore, buildings in areas with higher seismic fortification levels are found to have higher seismic capacities than those in areas with lower seismic fortification levels; 4) land-use type: The Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences constructed a database (scale: 1:100,000) for current land-use covering the Chinese mainland. Residential land in the database includes urban land, rural residential land, and other construction land, covering built-up areas in large, medium, and small cities, counties, towns, and rural regions. That is, the database includes construction land covered by all buildings in China. The investigation suggests that buildings constructed under strict government supervision in planned construction zones in the same township satisfy requirements imposed for seismic capacity; while self-built buildings account for a large proportion in unplanned construction areas, showing weak seismic resistances.

2.3 Division and classification of the seismic capacities of regional buildings

Through analysis of samples collected from in-situ investigation, the Chinese mainland was partitioned into grids (30″ × 30″), in each of which the seismic capacities of buildings were graded into 12 levels. The seismic capacity levels of buildings in each grid, that is, the overall seismic capacities of a region were calculated on the basis of five indices including population density and economic development. Then, the seismic vulnerability matrices of each type of buildings in the 12 types of regions were obtained by analysing predicted and actual seismic damage and vulnerability of buildings. Finally, the distribution of seismic capacities of buildings across China was attained by calculating the total areas of each type of buildings in each of the grid squares.

1) Mathematical model

To evaluate the overall seismic capacity of buildings in a 1 km × 1 km grid, it is firstly supposed that the comprehensive influencing factor for the seismic capacity is CIF_d, and the individual influencing factor for the seismic capacity is H_{di}. Data pertaining to various influencing factors were derived from 1) Chinese population data, 2) GDP data, 3) data on fortification intensities (VI, VII, VIII, and IX), 4) land-use planning data (construction and non-construction land), and 5) boundary data on administrative levels (provincial capitals, prefecture-level cities, counties, and county-level cities, townships, and villages), in one 1 km × 1 km grid square. The contribution of each factor influencing seismic capacities of buildings, that is, the weight is expressed by r_i. Therefore:

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

where and represent the value of the comprehensive influencing factor and the coefficient of different influencing factors, in a certain region; is the weight of the influencing factor; $\sum_{i=1}^{n} r_i = 1$.

2) Calculation of coefficients of population density and GDP

A research region is divided into provincial districts, prefecture-level cities, townships, and rural areas at first according to certain administrative division. By using provincial districts as the benchmark and the average-value method, the raw data are converted into comparable data series. That is to say, the average value V_{mav} of all gridded data (on population density and GDP) of all provincial districts in the research area is first computed, then data for each 1 km × 1 km grid square are separately divided by V_{mav}, thus obtaining a dimensionless data series. The data series can be used as the influence coefficient H_{di} , which is set to 1 when it is greater than 1. V_{mav} and H_{di} are calculated using:

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

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

where and separately denote the average value of gridded data and the data value of each 1 km × 1 km grid square in the provincial districts of the research area; refers to the coefficient of different influencing factors and represents data of each 1 km × 1 km grid square, of the research area.

3) Computation of coefficients of land-use type and seismic fortification intensity

Formulae (2) and (3) can be used to calculate coefficients of influencing factors including population density and GDP, while the coefficient of land-use type is calculated on the basis of urban and non-urban construction land. Seismic fortification of buildings can be graded into five levels, i.e. unfortified and fortification levels VI, VII, VIII, and IX. By conducting statistical analysis of historical seismic damage data and local fortifications across the research area, the coefficient of seismic fortification intensity can be obtained (Table 1).

Table 1 – Coefficients of seismic fortification intensity

Fortification intensity	**Unfortified**	**VI**	**VII**	**≥ VII**
Coefficient	0	0.5	0.8	1

4) Weight values

The analysis of influences of population density, GDP, land-use type, seismic fortification, and intensity of seismic damage to buildings indicated that seismic fortification intensity, GDP, and population density exerted the largest, moderate, and lowest influences on seismic capacities of buildings in different regions. Moreover, the influence of administrative division on the seismic capacity of structures was taken into consideration. For the purpose of determining weights of different influencing factors, the analytic hierarchy process (AHP) was used to quantify contributions of each factor to the seismic capacities of buildings.

AHP analysis and calculation are conducted using the following three steps: 1) constructing a hierarchical structural model; 2) building a judgment matrix; and 3) consistency testing. For matrices passing the consistency test, their weights were calculated using the geometric mean method using the following formula:

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

where r_i, a_{ij}, and n represent the weight vector of a matrix, an element in the ith row and jth column, and the order of the matrix, respectively.

Weights of each influencing factor were derived using the geometric mean method and Formula (4). The results are given in Table 2.

Table 2 – Values of weight coefficients

Influencing factor	**Population**	**GDP**	**Urban construction land**	**Seismic fortification intensity**
Weight coefficient	0.07	0.26	0.11	0.56

Considering the influence of administrative division and using the above division and classification approach, the influencing factors were adjusted, finally dividing the Chinese mainland into 12 types of regions on the basis of the seismic capacities of the buildings therein [2].

3. Seismic vulnerability of each type of structures

The vulnerability of a structure refers to the probability of occurrence of certain damage to the structures under seismic actions of given intensities. Experts across the world have been studying seismic vulnerability of buildings for a long time; however, previous methods mainly focus on individual buildings or are applied across small areas, showing high one-sidedness and limitation. While, the occurrence time, location, and range of affected areas of earthquakes are actually unknown. In the research, the seismic vulnerability matrices of various types of buildings in different regions were built by combining investigation and predictions of seismic damage, so as to measure seismic capacities of buildings in different regions.

1) Classification of structural types

Building structures in different regions needed to be classified as the seismic vulnerability matrices were constructed for different types of structures. Buildings in the Chinese mainland were classified into five categories by conducting lots of investigations on seismic damages, in-situ surveys of buildings, and referring to Code for Earthquake Loss Estimation and Its Information Management System (GB/T 9428-2014) [3]. These five types include high-rise, multi-storey framed, masonry, brick-wood structures, and others.

2) Data pertaining to seismic damage

Data from historical seismic damage events are primary sources for researchers to explore the occurrence and development of earthquakes and to study damage to engineering structures. Essential information, including occurrence time, location, and intensity of earthquakes, extent of damage to structures, the number of damaged structures, economic losses, and casualties represents the main facets of the data. Based thereon, data were collected from The Report of Estimated Seismic Damage in the Chinese Mainland [4-6], along with damage data of earthquakes happening in recent years. The summary of specific damage to buildings due to the earthquakes was the focus here: the damage ratios of the five degrees of damage to each type of structures subjected to earthquakes of different intensities were sorted according to the estimated results of buildings in the above report. On this basis, the seismic damage matrix was built for each structural type struck by earthquakes of different intensities in seismic regions. Additionally, the incomplete seismic damage matrix was complemented by adopting the improvement method for empirical seismic damage matrices [7].

3) Data for predicting seismic damages

By summarising seismic damage data, it is found that provinces including Yunnan, Gansu, and Sichuan as well as Xinjiang Uygur Autonomous Region and the Tibetan Autonomous Region are the primary regions suffering from the majority of destructive earthquakes in China; while by contrast, there are relatively few data pertaining to destructive earthquakes in north, south, and, north-east China, where buildings in cities do not experience strong earthquakes. To understand the seismic capacities of building structures, infrastructure and possible seismic damage thereto in the future, Chinese researchers have predicted seismic damages and evaluated seismic losses successively ever since the Seventh Five-Year Plan (from 1986 to 1990). The authors collected predicted seismic damage data for 20 cities (e.g. Jinjiang, Shishi, Fuzhou, Taiyuan, Dongying, Taian, and Daqing) to construct the seismic vulnerability matrices of buildings.

4) Prediction methods for seismic damage to building groups

Although data on seismic damages can be used to mirror seismic vulnerability of buildings in some cities, they are unable to show current seismic capacities of buildings in all regions. Therefore, for buildings in cities neither experiencing earthquakes nor having predicted seismic damage, their seismic damage was simulated by adopting mature prediction methods for building groups.

Empirical statistical methods, semi-empirical semi-theoretical methods, and intelligent agent-assisted decision methods for seismic damage prediction are among the common approaches used when forecasting seismic damage to building groups. The authors proposed a method for seismic damage prediction of building groups based on the existing seismic damage matrix in 2005 [8]. The method allows full use of sample data relating to existing and predicted seismic damage. Then the conditions of buildings in each area were analysed and compared with the sample data, thus obtaining the proximity between them. Eventually, the seismic vulnerability of structures in these areas was attained through simulation. After years of research, the method was improved by regarding fortification intensity as an important factor, thus coming up with a method for seismic damage prediction of building groups [9]. By distinguishing seismically fortified buildings from unfortified ones using data on existing historical and predicted seismic damage in cities, the method can be used to estimate a seismic damage matrix. The research was then used to predict the seismic vulnerability of building structures in different regions using the above methods and the existing and predicted seismic damage.

4. Seismic capacity indices of buildings

Apart from seismic performance of structures themselves, the overall seismic capacities of buildings in a region are also closely related to the distribution and proportions of each type of structure therein. The seismic vulnerability of different structural types in various regions was computed based on comprehensive division and classification data, thus attaining the average seismic damage index of various types of structures subjected to earthquakes of different intensities. The authors then established a mathematical model for distribution of the overall seismic capacity indices of buildings based on a 1 km × 1 km grid by considering structural types, construction areas, and seismic vulnerability under the influences of events of different seismic intensities.

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

where E_i represents the seismic capacity index of buildings in 1 km × 1 km grid squares under seismic intensity *i*; C_{ij} refers to the average seismic damage index of the *j*th building structure under seismic intensity *i*; A_j represents the total construction area covered by the *j*th structure.

The seismic damage index was proposed by earthquake engineering experts Liu Huixian et al. for quantifying degrees of structural damage. It provides a quantitative description for degrees of seismic damages to structures, which are generally indicated by figures in the range of 0~1. Table 3 lists the seismic damage indices corresponding to the five degrees of damage.

Table 3 – Relationships between seismic damage indices with degrees of seismic damage

Degree of damage	Generally intact	Slightly damaged	Moderately damaged	Seriously damaged	Destroyed
Median seismic damage index	0	0.2	0.4	0.7	1.0
Limit of seismic damage index	[0,0.1]	(0.1,0.3]	(0.3,0.55]	(0.55,0.85]	(0.85,1.0]

The average seismic damage index refers to the average degree of seismic damages to a certain building type in a city or region under earthquakes of given intensity, that is, the mean of seismic damage indices or average seismic damage index of building groups. It is calculated using the following formula:

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

where C_{ij} refers to the standardised seismic damage index of a certain type of building suffering from an earthquake of intensity *i*; D_j represents the median of seismic damage indices of buildings under an event of seismic intensity *j*; and $P(D_p \mid I)$ is the probability of occurrence of type-*p* damage to certain building structures under an event of seismic intensity *I*.

5. Conclusions

The distribution of seismic capacities of buildings on the Chinese mainland was analysed. The distribution map for seismic capacity indices of buildings in some provinces under earthquakes of different intensities was drawn. The following conclusions can be drawn:

1) Apart from building themselves, the seismic capacities of buildings are also affected by multiple social factors including administrative division, seismic fortification level, population density, economic development, and land-use type. The research classified seismic capacities of buildings in the Chinese mainland into 12 levels by analysing their key influencing factors.

2) The seismic vulnerability matrices of buildings can be used as a comprehensive measure denoting the seismic capacities of buildings in a city or region. The seismic vulnerability matrices of various types of buildings in different regions were constructed by using the most of existing seismic damage data, predicted seismic damage, and mature methods for predicting seismic damage to building groups.

3) A mathematical model for overall seismic capacity index of buildings based on 1 km × 1 km grid squares was established by taking average seismic damage indices and distribution areas covered by different types of buildings into consideration. Through simulation, the distribution of seismic capacity indices of buildings suffering earthquakes of different intensities was mapped. The map macroscopically displays the current seismic capacities of buildings in various regions and therefore provides a basis for decision-making for the government in construction planning.

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