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## Comparative analysis of the earthquake disaster risk of cities in Eastern China based on lethal levels – a case study of Yancheng City, Suqian City and Guangzhou City

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### ABSTRACT

Earthquake disaster risk analyses provide significant scientific guidance for reducing earthquake disaster losses etc. The current commonly used method is based on the vulnerability of different types of buildings to evaluate, and may ignore the difference between the seismic resistance of the same type of buildings in different areas. The lethal level considers a series of reasons such as different types of buildings, resulting in different capacities for casualties, the lethal levels of the cities in the same subregion are considerably different and exhibit obvious distribution characteristics. In Yancheng and Suqian, the lethal levels in urban areas are lower than those in rural areas, but the lethal levels in Guangzhou show the opposite trend (the lethal levels are higher in urban areas than in other towns and rural areas). The average lethal level in Guangzhou is 0.3856, that in Suqian is 0.5844, and that in Yancheng is 0.5912. This study based on the lethal levels, conduct a comparative analysis of the earthquake disaster risk of cities throughout eastern China, and a map of the earthquake disaster risk in each city is obtained. The overall lethal level and risk in Guangzhou is much lower than those in Yancheng and Suqian. The main influencing factors in the different cities also diverge. One reason for the lower lethal levels and risk in Guangzhou is that most of the brick-concrete structures are equipped with ring beams and structural columns; conversely, Yancheng and Suqian exhibit higher lethal levels and risk because the brick-concrete structures have ring beams but no structural columns. These maps provide a technical reference and solid scientific and technological support for further earthquake disaster risk analyses and for disaster prevention, mitigation and disaster relief planning, and this method improves the accuracy of rapid postearthquake assessment.

**Abbreviation:** PSHA: probabilistic seismic hazard assessment; DSHA: deterministic seismic hazard assessment; ANNs: Artificial Neural Networks; FL: Fuzzy Logic; ML: Machine Learning; MLP:

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Building type; lethal level; earthquake disaster risk; differentiation; field survey

Multi-Layer Perceptron; Type-2 FL: Type-2 fuzzy logic system; RCa and RCb: Two classifications of Reinforced concrete structure; Ba: Fortified Brick-concrete structure; Bb: Unfortified Brick-concrete structure; CLactual: the actual lethal level of a certain type of building; CLmax and CLmin: the upper and lower limits of the lethal level interval range; CLall: the lethal level of the region based on the buildings; CLtown: the overall lethal level of the town; CLtownship: the lethal level of the township; CLcountryside-i: the lethal level of the i-th administrative village; R: the earthquake disaster risk; H: the earthquake hazard (related to factors such as geological parameters, ground motion parameters and active faults); V: the building vulnerability, and E is the exposed population (the proportion of the population exposed to an earthquake disaster, that is, the number of permanent residents in the study area); LL: the lethal level of the area

## Introduction

Being prone to earthquakes throughout the nation, China suffers from potential seismic risks everywhere. Statistics show that approximately 95% of all casualties in earthquakes were caused by the destruction of buildings (Sun and Zhang 2017). However, due to differences in the natural conditions, economic development, resource distribution, and seismic fortification in different regions, buildings are obviously diverse and have significantly variable levels of seismic resistance. This disparity is responsible for the difference in disaster losses between the western and eastern earthquake-prone areas and thus cannot be ignored.

Therefore, it is possible to identify the earthquake resistance of an area based on the attributes of the buildings, geography, geomorphological landforms, and traffic environment in that region. In particular, the current earthquake resistances of buildings in different regions are particularly important for establishing earthquake prevention and mitigation strategies, understanding the threat of earthquake disasters, preparing for pre-earthquake emergencies, and carrying out targeted measures. Acquiring such information also makes it possible to quickly grasp the earthquake risk situation during an earthquake and therefore take targeted emergency countermeasures.

The risk is the expected losses of hazard and vulnerability, among them, the hazard is a potential threat to a particular place, the vulnerability is the conditions determined by various factors that can increase the susceptibility of any community to the impact of the hazard, and in literature, there are many models and tools have been widely employed for seismic hazard and risk assessment, such as United States Geological Survey (USGS) national seismic hazard models, European seismic hazard model (ESHM13), Earthquake Model of the Middle East (EMME14), the Global Hazard Models, and Global Earthquake Model (Woessner et al. 2015; Danciu et al. 2018; Giardini et al. 2018; Pradhan et al. 2018). In general, these models can be divided into two major aspects, such as probabilistic and deterministic seismic hazard assessment (PSHA and DSHA) (RADIUS 2012), which consists of a hazard estimation, a vulnerability evaluation and an exposure analysis (Blaikie et al. 2014; Burton and Silva 2016; Jayaram et al. 2012; Pagani et al. 2014; Rossetto et al. 2015; Silva

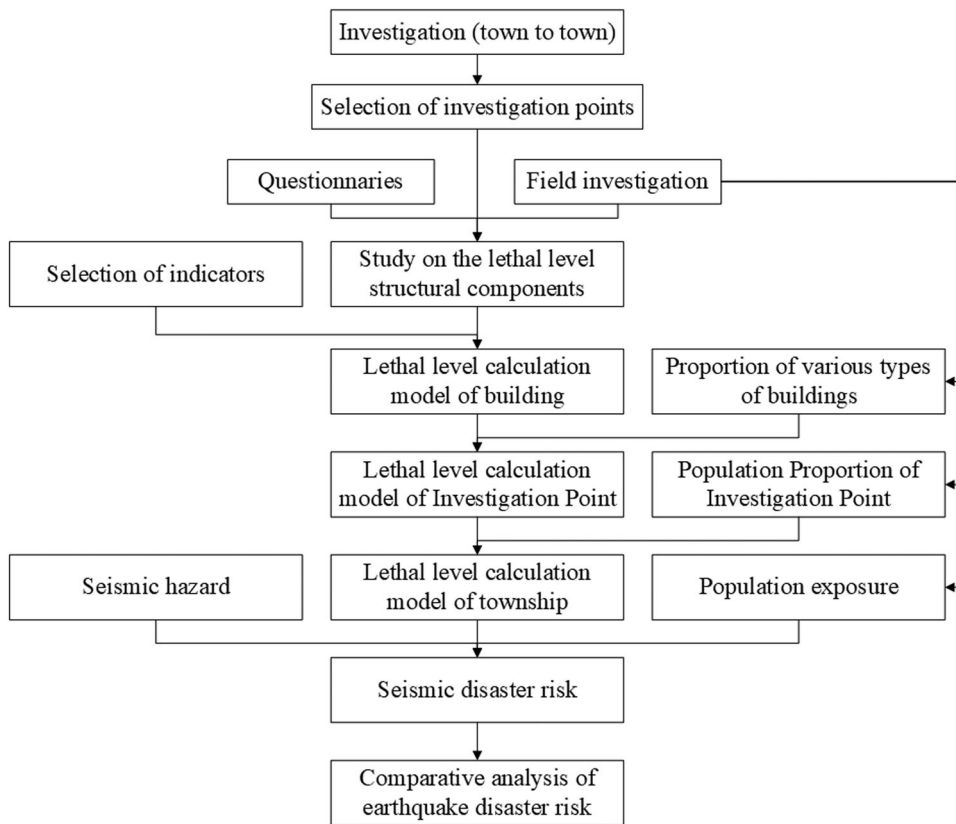
2016; Frolova et al. 2017; Šipoš and Hadzima-Nyarko 2017; Martins and Silva 2018; Buyuksarac et al. 2021; Crowley et al. 2020; Dolce et al. 2020; Kohrangi et al. 2021; Papadopoulos and Bazzurro 2021).

Among them, PSHA requires the quantification of the uncertainties in earthquake magnitude, location, recurrence, and effects in ground shaking in the seismic hazard estimation, moreover, the accuracy of the probabilistic analysis based on the uncertainties can be characterized, there are some limitations such as data scarcity, invalid physical model and mathematical (Scawthorn and Chen 2002), poor quantification of uncertainties, et al., meanwhile, DSHA is an useful for creating an improved model, it is generally applying the assumed earthquake events in a specific region (Shah et al. 2012), and it have very easy methodology, however, DHSA does not provide any information on the likelihood of recurrence of the controlling earthquake and have no strong solid physics roots, it makes the model lack of consideration of uncertainties, and the result may poor. In addition, whether it is PSHA or DSHA method, it requires large amounts of various input data, which are impossible to collect in many developing countries.

Therefore, other relatively simple and efficient evaluation methods are needed, due to the GIS technology provide new ideas for research of the earthquake hazard and susceptibility analysis, many researchers use GIS-based models for seismic hazard and risk assessment, the model is to integrate various relevant data with the concepts of risk assessment by considering three elements, namely, hazard source, damage level to objects, and threat (Tsai and Chen 2010), the method is one of the most popular methods in seismic risk assessment (Smith 2001), and it is efficient and quite feasible.

In summary, the focus of this method is the correlation between the vulnerability parameters and seismic vulnerability assessment, it including Artificial Neural Networks (ANNs), Fuzzy Logic (FL), Machine Learning (ML), and probabilistic approaches versus analytical methodologies such as static non-linear analysis (Pushover analysis) that produce capacity curves and are used along with seismic-demand spectrum (Harirchian et al. 2021a), such as, Harirchian et al. based on the Multi-Layer Perceptron (MLP) Neural Network architecture and smartphone app to obtain an optimal prediction of the damage state of RC buildings, the results show the practicability and efficacy of the selected ANN approach for classifying actual damage grade based on structural damage (Harirchian et al. 2021b, 2021c), xin et al. uses finer urbanity level population and building-related statistics data to develop a high-resolution residential building stock model for mainland China, and based on the result of residential building stock for seismic risk assessment (Xin et al. 2021), li et al. developed building taxonomy for the Eastern Himalayas and estimated the distribution of building types in each town based on a field survey and local census data, and built a structure vulnerability model and mortality vulnerability model for each building type and simulated the loss distribution based on an earthquake scenario and probabilistic seismic hazards (Li et al. 2021), Aydin et al. based on the tectonic setting, seismicity and the probabilistic seismic hazard curves of Van, determined the risk priorities for buildings in all districts via rapid seismic assessment for reinforced-concrete and masonry buildings, Zhang et al. based on a three-step data collection method, and presented upgradeable building typology for the seismic





**Figure 1.** The flowchart map of seismic disaster risk assessment.

fragility assessment of building blocks, and proposed a new economic loss model and casualty model for urban disaster risk assessment (Zhang et al. 2021), Allali et al. developed a methodology based on a single-antecedent weighted fuzzy rule integrated with a general aspects to optimize the rule weights, to derive the global damage level for postearthquake seismic assessment of buildings (Allali et al. 2018), Ketsap et al. used three-stage fuzzy rule-based model to calculate total seismic risk by integrating three major risk factors in a hierarchical structure along with their uncertainties using a fuzzy rule based model and finally prioritize building retrofit (Ketsap et al. 2019), Harirchian and Lahmer based on interval Type-2 FL to improved rapid visual earthquake hazard safety evaluation of existing buildings, and rapid evaluation of earthquake hazard safety of existing buildings (Harirchian and Lahmer 2020a, 2020b).

From this, we can also find that no matter which method it is, conducting research on and analyzing the seismic capacities and vulnerabilities of different buildings, studying the natural geographical environments of different regions, and quantifying the seismic capacities of buildings in different regions (such as the building vulnerability and lethal level) are important tasks for seismic risk assessment.

However, different researchers have found that, even under similar earthquake magnitudes, population densities, geographical and geomorphological environments, and building vulnerability levels, the number of casualties varies greatly, such as

between the 2014 Ludian and Jinggu earthquakes (He et al. 2015; Hong et al. 2015). The reason is that while different types of buildings may have the same level of vulnerability, after an earthquake, the ability to cause casualties may differ substantially; that is, different buildings have different lethal level. After an earthquake, the assessment of casualties based only on the vulnerabilities of buildings may introduce errors; therefore, it is necessary to quantitatively analyze the regional seismic capacity based on lethal level.

Nevertheless, the existing earthquake disaster risk assessment methods are still based on vulnerability levels, which may result in erroneous results. This article is based on the range and calculation model of the lethal level of buildings, by conducting field investigations, obtain the lethal level results in 3 cities, and build a risk assessment model based on the lethal level, obtain the evaluation results of different cities, carry out corresponding comparative analysis, obtain the main influencing factors of earthquake disaster risk in different cities, at the same time, the methodology provides novel insights for ongoing earthquake disaster risk assessment research. The flowchart is shown in Figure 1.

## **Analysis of the influencing factors of buildings' lethal levels**

### ***Leapfrogging in the construction era***

Different administrative areas are affected by various factors, such as administrative divisions and levels of economic development, resulting in the coexistence of old and new buildings whose conditions are different; correspondingly, their levels of seismic vulnerability and lethality also differ. At the same time, buildings also exhibit variable seismic performance due to different standards and codes used for building structures constructed in different years. For example, whether a building structure is fortified against earthquakes will dictate how that structure behaves in an earthquake. Buildings equipped with some measures of seismic fortification or seismic reinforcement fare significantly better than buildings without such measures under seismic excitation; likewise, the lethal levels of fortified buildings are lower than those of unfortified buildings. Therefore, the actual lethal level of an area can also be obtained more accurately by considering the effects of buildings' ages on their levels of lethality.

### ***Regional differences in the lethal level of buildings***

Because China spans a vast area, it displays obvious differences in the natural environment, geographical conditions, cultural traditions, ethnic characteristics and economic development levels among various regions; as a consequence, the seismic resistance of buildings presents obvious regional characteristics. For example, in eastern China, which features a developed economy, the proportion of newly constructed buildings is increasing, the quality of construction is superior, and the proportion of structures with earthquake-resistant fortification is high. In contrast, in central and western China, the economy is underdeveloped, the proportion of newly constructed buildings is small (the proportion of old buildings is high), the construction quality is

poor, and the proportion of buildings with seismic fortification is low. Furthermore, even in the same area, the differences between urban and rural structures are obvious, and the number of engineering structure types in cities and towns continues to increase. In economically underdeveloped rural areas, there is usually a single structure type, the anti-seismic structural measures are not perfect, and the construction quality is difficult to supervise. Comparatively, rural areas in economically developed areas have more types and greater numbers of structures and stronger anti-seismic structural measures.

Generally, the characteristics of buildings in the same area have certain similarities, but even within the same region, there are certain differences between provinces; therefore, if an analysis of the lethal level of a building is based only on its geographical location, errors may arise. This article carries out a comparative analysis of the lethal levels and earthquake disaster risks of different cities in the same subregion and constructs an earthquake disaster risk assessment method based on the lethal level.

## **Distribution of the regional lethal level**

### ***Method for investigating the lethal level***

This paper selects the results of field surveys in typical cities in different provinces throughout eastern China and conducts a comparative analysis based on the lethal level to identify the similarities and differences between those cities. The research area includes 3 cities in eastern China, namely, Yancheng and Suqian in Jiangsu Province and Guangzhou in Guangdong Province.

The field survey method adopts the "town to town" method (that is, a field survey is conducted in each administrative unit at the town level, and the streets in the urban area are determined according to the town level), and 3–4 administrative villages in each town are selected as survey points. The survey points include 1 downtown area (central area) and 2–3 representative administrative villages. The contents of the survey include the structural characteristics, construction method, building materials, adhesive types, foundation type and form, roof type, construction age, and connection methods of the various sampled building structures at the survey points; the survey also includes the geographical and geomorphological environmental conditions in the area, traffic and road conditions, ancillary building structure conditions, etc.

However, Due to the variability of climatic conditions, geographical environments, economic conditions, building materials, construction methods, and political factors, the types of buildings are broadly diverse, resulting in obvious differences among the building types in different regions. Generally, buildings can be divided into several types according to their predominant material, such as wood structures, civil structures, brick-wood structures, brick-concrete structures, reinforced concrete structures, and steel structures. A large number of field investigations reveal that even for the same building type in the same area, due to differences in their building materials, construction methods, use functions, wall types, adhesive types, and foundations, obvious differences arise under different disaster conditions, the types of buildings

**Table 1.** Intervals and influencing factors of the lethal levels of buildings.

Building structure type			
Building type	Secondary classification	Influencing factors	Lethal level range
Steel structure		Construction measures, foundation type, construction age, use type	0.05–0.15
Reinforced concrete structure	RCa RCb	Structural measures, foundation type, construction age, height	0.1–0.3
Wood structure	Wa Wb	Structural measures, foundation type, construction age, structural style	0.2–0.4
Brick-concrete structure	Ba (Fortified) Bb (Unfortified)	Structural measures, foundation type, construction age, use type, height	0.25–0.7
Brick-wood structure		Structural measures, foundation type, construction age, structural style	0.6–0.9
Civil structure		Construction measures, foundation type, construction age, building materials	0.7–0.95
Stone-wood structure		Wall type, foundation type, construction age, building materials	0.55–0.9
Adobe structure		Wall type, foundation type, construction age, building materials	0.85–1

(Based on the results of previous research, the range of lethality levels of various types of buildings are obtained, It is a non-equal interval range with overlapping areas between each other. For details, please refer to the relevant research results of the author of this article.)

are uniformly classified according to the structural materials as follows: steel structures, reinforced concrete structures, brick-concrete structures (including fortified brick-concrete and unfortified brick-concrete), brick and wood structures, wood structures, civil structures and traditional structure types unique to each region (determined according to the actual situation of the survey area).

### **Method for calculating the regional lethal level**

The lethal level ranges of different types of buildings are based mainly on the author's previous research results (Xia et al. 2020; Xia 2020), as shown in Table 1. Based on historical seismic data, we calculated the range of lethal levels for different types of buildings, it turns out that the interval range of each type of building is a non-equal inter-zone range, and there are overlapping areas between each other, in other words, the actual lethal level of a certain type of building may not necessarily be lower than other types of buildings due to the influence of the construction method, construction quality, and construction age, for example, the lethal level of an undefended brick-concrete structure is not necessarily lower than that of a newly constructed brick-wood structure of good quality. At the same time, the influencing factors of the lethal level of each type of building are also different, in this way, based on the lethal level

range of each type of building and different influencing factors, it is able to perform quantitative calculations of different types of buildings in field surveys. Based on the interval range of each type of building and the ratio of influence weights of each influencing factor, a method for calculating the actual lethal level of each type of building is developed, as shown in [equation 1](#):

$$CL_{\text{actual}} = CL_{\text{max}} - \sum_{i=1}^n (CL_{\text{max}} - CL_{\text{min}}) \cdot w_i \cdot w_{ij} \quad (1)$$

In [Equation 1](#),  $CL_{\text{actual}}$  is the actual lethal level of a certain type of building,  $CL_{\text{max}}$  and  $CL_{\text{min}}$  are the upper and lower limits, respectively, of the lethal level interval for a certain type of building,  $n$  is the number of factors affecting the lethal level of a certain type of building selected according to the actual conditions of the types of buildings in the survey area,  $w_i$  is the ratio of the weights of the  $i$ -th type of influencing factor affecting the building selected based on the actual situation of the building, and  $w_{ij}$  is the weight ratio for the  $j$ -th building structure and the  $i$ -th type of influencing factor affecting the building selected based on the actual situation of the building.

Based on the lethal levels of various types of buildings and the proportion of each type of building, a calculation model is established for the overall lethal level of the survey area, as shown in [equation 2](#):

$$CL_{\text{all}} = \sum_{i=1}^n CL_{\text{actual}-i} \cdot P_i \quad (2)$$

where  $CL_{\text{all}}$  is the lethal level of the region based on the buildings,  $CL_{\text{actual}-i}$  is the actual lethal level of the  $i$ -th type of building in the region, and  $P_i$  is the proportion of the  $i$ -th type of building.

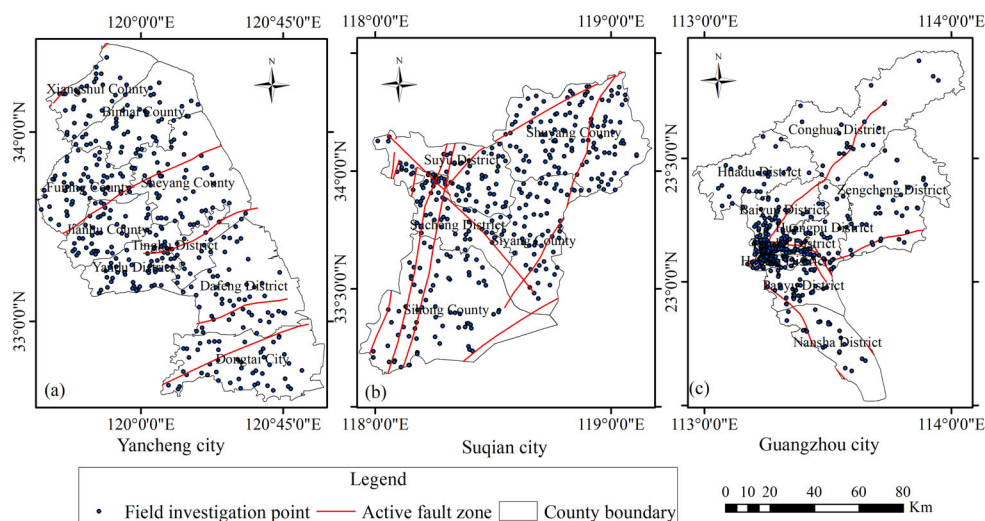
On the basis of the lethal level at each survey point, a method for calculating the town-level lethality is proposed based on the relative proportions of the population, as shown in [Equation 3](#):

$$CL_{\text{town}} = \alpha \cdot CL_{\text{township}} + \beta \cdot \sum CL_{\text{countryside}-i} \cdot \gamma_i \quad (3)$$

where  $CL_{\text{town}}$  is the overall lethal level of the town,  $CL_{\text{township}}$  is the lethal level of the township,  $CL_{\text{countryside}-i}$  is the lethal level of the  $i$ -th administrative village in the administrative township,  $\alpha$  is the ratio of the population of the town to the population of the whole township,  $\beta$  is the ratio of the population of the administrative village to the population of the whole town,  $\alpha + \beta = 1$ , and  $\gamma_i$  is the ratio of the population of the  $i$ -th administrative village to the total population of the administrative village.

### **Method for calculating the earthquake disaster risk level**

To analyze the earthquake risk, the current assessment method is adopted, where the risk is calculated as earthquake disaster risk = earthquake site hazard \* building



**Figure 2.** Distribution map of the field survey points in 3 cities.

vulnerability \* crowd exposure (Chen et al. 1997; Nie et al. 2002; Federal Emergency Management Agency 2009):

$$R = H \times V \times E \quad (4)$$

where  $R$  denotes the earthquake disaster risk,  $H$  is the earthquake hazard (related to factors such as geological parameters, ground motion parameters and active faults),  $V$  is the building vulnerability, and  $E$  is the exposed population (the proportion of the population exposed to an earthquake disaster, that is, the number of permanent residents in the study area).

On the basis of this method, this paper calculates the vulnerability of buildings using the lethal level and finally determines the earthquake disaster risk level at a particular site:

$$R = H \times LL \times E_{\text{actual}} \quad (5)$$

where  $H$  is the earthquake hazard,  $LL$  is the lethal level of the area, and  $E_{\text{actual}}$  is the number of permanent residents.

## Results





### *Distribution of the lethal level in Yancheng City, Jiangsu Province*

#### *Survey points and main building types in Yancheng*

As shown in Figure 2a, Yancheng city encompasses 9 districts and counties, including a total of 143 townships. According to the sampling survey method, there are a total of 392 sample survey points, the distribution of which achieves full coverage at the township level. The survey point distribution is relatively uniform, and thus, the




**Table 2.** Types and specific characteristics of the buildings in Yancheng.

Building type		Field survey photos	Specific characteristics
Brick-wood structure	a		The walls are 24 cm thick, the bonding material is cement mortar or lime mortar, and the gravel foundation is approximately 1 m
	b		The walls are 18 cm thick, the bonding material is lime mortar or loess mud, and the gravel foundation is approximately 1 m
Brick-concrete structures	a		With ring beams, structural columns, cast-in-place roof, 24 cm thick walls, and a 1.5 m concrete foundation
	b		With ring beams, structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m concrete foundation or brick foundation

(continued)



Table 2. Continued.

Building type	Field survey photos	Specific characteristics
Reinforced concrete structure	<div>c</div> 	With ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m brick foundation or gravel foundation
	<div>d</div> 	No ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m brick foundation or gravel foundation
		Standard frame structure, concrete frame, complete beam and column system, concrete foundation

(Specific characteristics of each building type obtained based on field investigation)

lethal level obtained by averaging the survey points of each township can represent the average situation of each township.

As shown in Table 2, the buildings in Yancheng mainly include 3 categories and 7 subcategories, the results as follow:

1. The brick-wood structures in Yancheng are mainly distributed in rural areas, it mainly divided into 2 types, the brick-wood structure (a), the walls are 24 cm thick, the bonding material is cement mortar or lime mortar, and the gravel foundation is approximately 1 m; brick-wood structure (b), the walls are 18 cm

thick, the bonding material is lime mortar or loess mud, and the gravel foundation is less than 1 m, and the construction quality is poor, the height of the building is generally 1 storey, in contrast, the number of civil structures is small; generally, no people live in these buildings, which are mostly warehouses.

2. The brick-concrete structures are distributed in both urban and rural areas in Yancheng, and the distribution (both urban and rural areas) have obvious characteristics. Generally, the brick-concrete structures in the urban areas are predominantly fortified brick-concrete structures with ring beams and structure columns. At the same time, there is a certain number of unfortified brick-concrete structures. Moreover, although the rural areas also contain a large number of brick-concrete structures with ring beams, the structures are not equipped with structural columns, and there is a clear difference in their seismic resistance level from that of fortified brick-concrete structures;

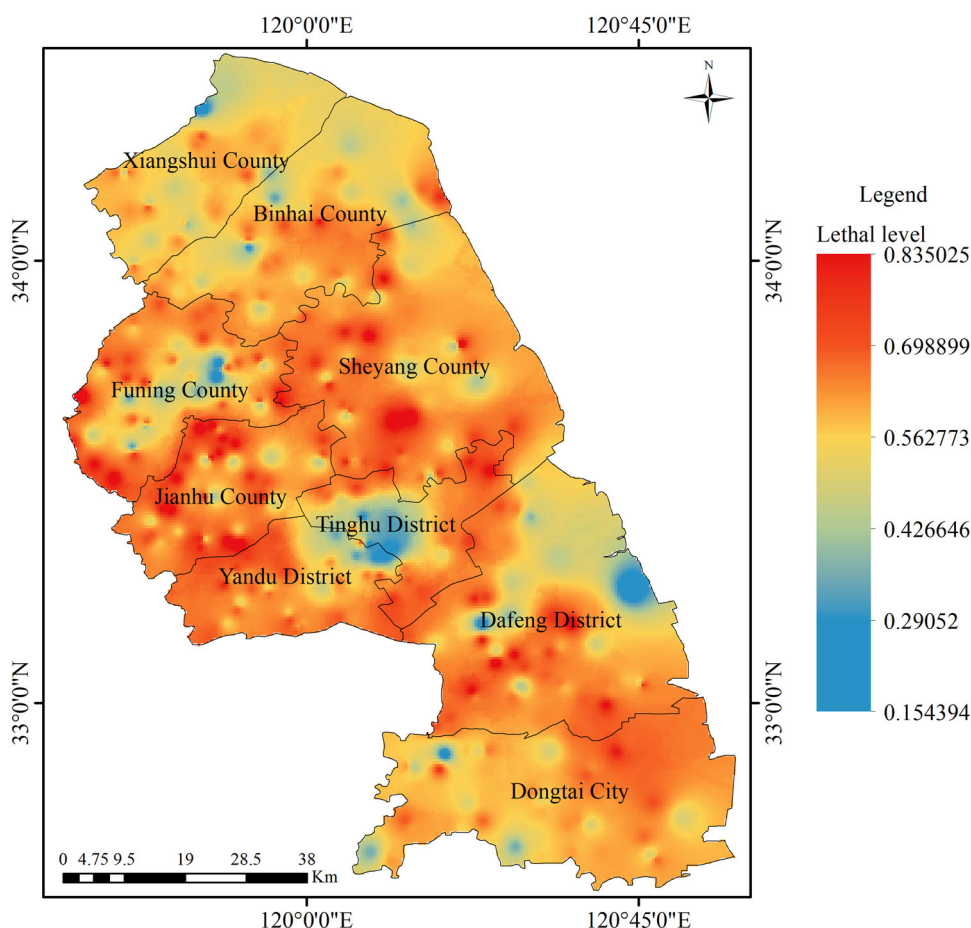
It mainly divided into 4 types, the brick-concrete structures (a), which is with ring beams, structural columns, cast-in-place roof, 24 cm thick walls, and a 1.5 m concrete foundation, the construction age is generally after 2010; the brick-concrete structures (b), which is with ring beams, structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m concrete foundation or brick foundation, the construction age is generally between 1990 and 2010; the brick-concrete structures (c), which is with ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m or 1.2 m brick foundation or gravel foundation, the construction age is generally between 1970 and 2000; the brick-concrete structures (d), which is with no ring beams, no structural columns, prefabricated slab roof, 24 cm or 18 cm thick walls, 1.5 m or 1 m brick foundation or gravel foundation, the construction age is generally before 1980; generally speaking, different types of brick-concrete structures have large differences in their seismic resistance, and the building height of each type of brick-concrete structure is generally 2 storey.

- The reinforced concrete structure in Yancheng are mainly distributed in urban areas, it is standard frame structure, the building structure is a concrete frame, with a complete beam and column system, the beam and column diameter is generally above 50 cm, the foundation is also a standard concrete foundation, and the building height is generally above 5 storey.

### *Lethal level distribution in Yancheng*

As shown in [Figure 3](#), the lethal level distribution in Yancheng is obvious. The lethal level of the entire city is approximately 0.5 with low values in the urban areas and high values in the rural areas. The areas with low lethal levels in Yancheng city are distributed in 3 main areas, namely, Tinghu District and Funing County and the eastern part of Dafeng District. Taking Tinghu District as the dividing line, the lethal level in the northern region is higher than that in the southern region. The lethal level of various districts and counties are not obvious.

The areas with high lethal levels and weak earthquake-resistant fortifications are mainly distributed in the western area of Yancheng city, including parts of Jianhu



**Figure 3.** Distribution of the lethal level in Yancheng.





County and Yandu District. There are some areas with a low lethal level in every district and county; these levels are generally concentrated in the county seat of each district or county or the main area of each town, as well as in newly established development districts and other administrative areas in some districts and counties. These areas have relatively good seismic resistance and low lethal levels. In contrast, the areas with high lethal levels are mainly distributed in rural areas.

### ***Distribution of lethal level in Suqian City, Jiangsu Province***

#### ***Survey points and main building types in Suqian City***

As shown in Figure 2b, Suqian city encompasses 5 districts and counties, including a total of 149 townships. According to the sampling survey method, the number of survey points is 368, the distribution of which achieves full coverage at the township level. The survey point distribution is relatively uniform, and thus, the lethal level obtained by averaging the survey points of each township can represent the average situation of each township.




Table 3. Types and specific characteristics of the buildings in Suqian.

Building type	Field survey photos		Specific characteristics
Brick-wood structure	a		The walls are 24 cm thick, the bonding material is cement mortar or lime mortar, and the gravel foundation is approximately 1 m
	b		The walls are 18 cm thick, the bonding material is lime mortar or loess mud, and the gravel foundation is approximately 1 m
Brick-concrete structures	a		With ring beams, structural columns, cast-in-place roof, 24 cm thick walls, 1.5 m concrete foundation
	b		With ring beams, structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m concrete foundation or brick foundation

(continued)



Table 3. Continued.

Building type	Field survey photos	Specific characteristics
	<div>c</div> 	With ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m brick foundation or gravel foundation
	<div>d</div> 	No ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m brick foundation or gravel foundation
Reinforced concrete structure		Standard frame structure, concrete frame, complete beam and column system, concrete foundation

(Specific characteristics of each building type obtained based on field investigation).

As shown in Table 3, the buildings in Suqian mainly include 3 categories and 7 subcategories, the results as follow:

1. The brick-wood structures in Suqian are mainly distributed in rural areas, it mainly divided into 2 types, the brick-wood structure (a), the walls are 24 cm thick, the bonding material is cement mortar or lime mortar, and the gravel foundation is approximately 1 m; brick-wood structure (b), the walls are 18 cm thick, the bonding material is lime mortar or loess mud, and the gravel foundation is less than 1 m, and the construction quality is poor, the height of the building is generally 1 storey.
2. The brick-concrete structures are distributed in both urban and rural areas in Suqian, It mainly divided into 4 types, the brick-concrete structures (a), which is with ring beams, structural columns, cast-in-place roof, 24 cm thick walls, and a 1.5 m concrete foundation, the construction age is generally after 2012; the brick-concrete structures (b), which is with ring beams, structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m concrete foundation or brick foundation, the construction age is generally after 1990; the brick-concrete structures (c), which is with ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m or 1.2 m brick foundation or gravel foundation, the construction age is generally after 1970; the brick-concrete structures (d), which is with no ring beams, no structural columns, prefabricated slab roof, 24 cm or 18 cm thick walls, 1.5 m or 1 m brick foundation or gravel foundation, the construction age is generally before 1980; generally speaking, different types of brick-concrete structures have large differences in their seismic resistance, and the building height of each type of brick-concrete structure is generally 2 storey.
3. The reinforced concrete structure in Suqian are mainly distributed in urban areas, it is standard frame structure, the building structure is a concrete frame, with a complete beam and column system, the beam and column diameter is generally above 50 cm, the foundation is also a standard concrete foundation, and the building height is generally above 5 storey.

#### *Lethal level distribution in Suqian*

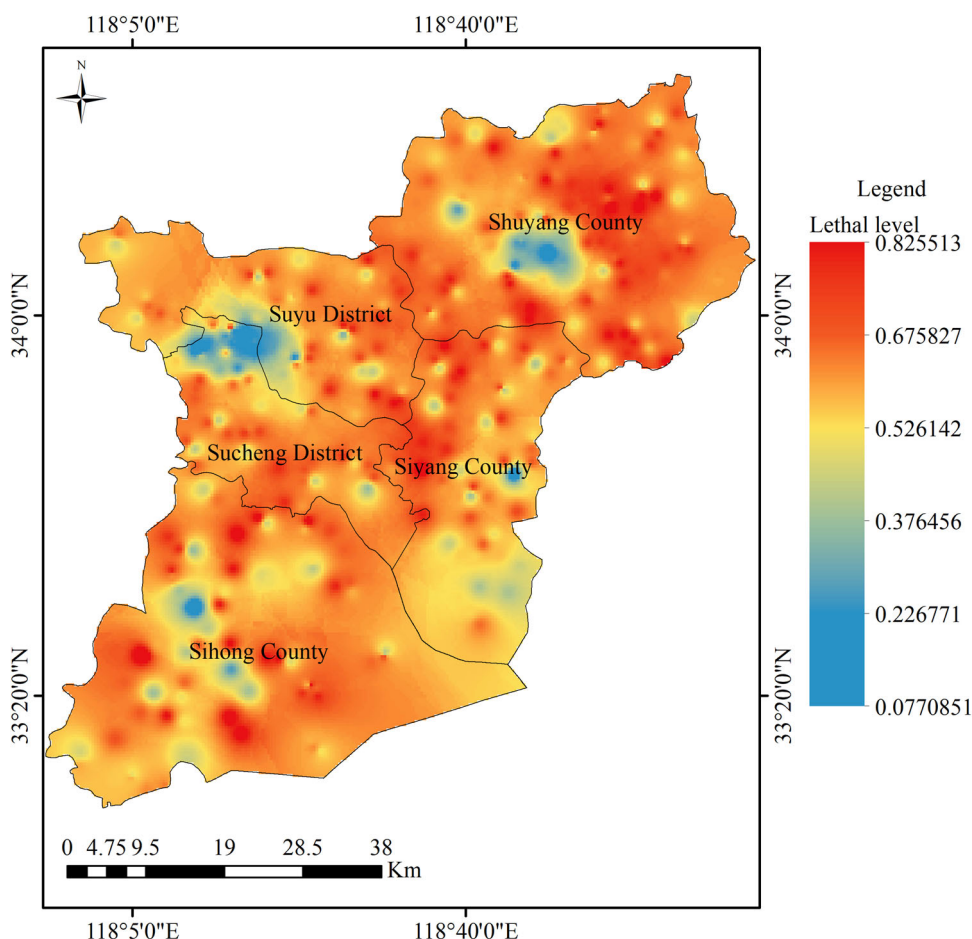
As shown in Figure 4, the lethal level in Suqian city is approximately 0.6, and the distribution characteristics are obvious, with low values distributed in 3 main areas: Suyu District, Sucheng District and Shuyang County.

The lethal levels in the remaining districts and counties are high, and the distribution of lethal levels in Suqian city presents obvious administrative regional distribution characteristics. For example, Suyu District and Shuyang County, which are located in urban areas, have good economies and strong earthquake-resistant fortifications, whereas the lethal levels in other regions are average, among which there is no obvious difference.

#### *Distribution of lethal levels in Guangzhou City, Guangdong Province*

##### *Survey points and main building types in Guangzhou*

As shown in Figure 2c, Guangzhou city involves 11 districts and counties, including a total of 171 townships. The number of survey points is 431, the distribution of which



**Figure 4.** Distribution of the lethal level in Suqian.




achieves full coverage at the township level. The survey point distribution is relatively uniform, and thus, the lethal level obtained by averaging the survey points of each township can represent the average situation of each township.

As shown in Table 4, the buildings in Guangzhou mainly include 4 categories and 9 subcategories, the results as follow:

1. The brick-wood structures in Guangzhou are mainly distributed in rural areas, it mainly divided into 2 types, the brick-wood structure (a), the walls are 24 cm thick, the bonding material is cement mortar or lime mortar, and the gravel foundation is approximately 1 m, the height of the building is generally 2 storey; brick-wood structure (b), the walls are 18 cm thick, the bonding material is lime mortar or loess mud, and the gravel foundation is less than 1 m, and the construction quality is poor, the height of the building is generally 1 storey.
2. The brick-concrete structures are distributed in both urban and rural areas in Guangzhou, It mainly divided into 5 types, the brick-concrete structures (a), which is with ring beams, structural columns, cast-in-place roof, 24 cm thick






Table 4. Types and specific characteristics of buildings in Guangzhou.

Building type		Field survey photos	Specific characteristics
Brick-wood structure	a		The walls are 24 cm thick, the bonding material is cement mortar or lime mortar, and the gravel foundation is approximately 1 m
	b	 	The walls are 18 cm thick, the bonding material is lime mortar or loess mud, and the gravel foundation is approximately 1 m

(continued)

Table 4. Continued.

Building type		Field survey photos	Specific characteristics
Brick-concrete structures	a		With ring beams, structural columns, cast-in-place roof, 24 cm thick walls, 1.5 m reinforced concrete foundation
			
	b		With ring beams, structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m brick foundation

(continued)

Table 4. Continued.

Building type	Field survey photos	Specific characteristics
c		With ring beams, no structural columns, cast-in-place roof, 24 cm thick walls, 1.5 m concrete foundation or brick foundation
d		With ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m brick foundation
e		No ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m brick foundation

(continued)

Table 4. Continued.

Building type	Field survey photos	Specific characteristics
		
Reinforced concrete structure		Standard frame structure, concrete frame, complete beam and column system, concrete foundation
		

(continued)





Table 4. Continued.

Building type	Field survey photos	Specific characteristics
Civil structure	<div></div>	Without wooden pillar support, sloping roof, mud brick or adobe walls, bonded or unbonded soil
	<div></div>	

(continued)

Table 4. Continued.

Building type	Field survey photos	Specific characteristics
Road characteristics	<div></div>	Small spacing between buildings, many external hanging objects and ancillary structures

(Specific characteristics of each building type obtained based on field investigation).

- walls, and a 1.5 m concrete foundation, the construction age is generally after 2000; the brick-concrete structures (b), which is with ring beams, structural columns, prefabricated slab roof, 24 cm thick walls, and a 1.5 m brick foundation, the construction age is generally after 1990; the brick-concrete structures (c), which is with ring beams, no structural columns, cast-in-place roof, 24 cm thick walls, and a 1.5 m concrete foundation or brick foundation, the construction age is generally after 1990; the brick-concrete structures (d), which is with ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m or 1 m brick foundation, the construction age is generally after 1980; the brick-concrete structures (e), which is no ring beams, no structural columns, prefabricated slab roof, 24 cm thick walls, 1.5 m or 1 m brick foundation, the construction age is generally after 1970; generally speaking, different types of brick-concrete structures have large differences in their seismic resistance, and the building height of each type of brick-concrete structure is generally above 2 storey.
3. The reinforced concrete structure in Guangzhou are mainly distributed in urban areas, it is standard frame structure, the building structure is a concrete frame,

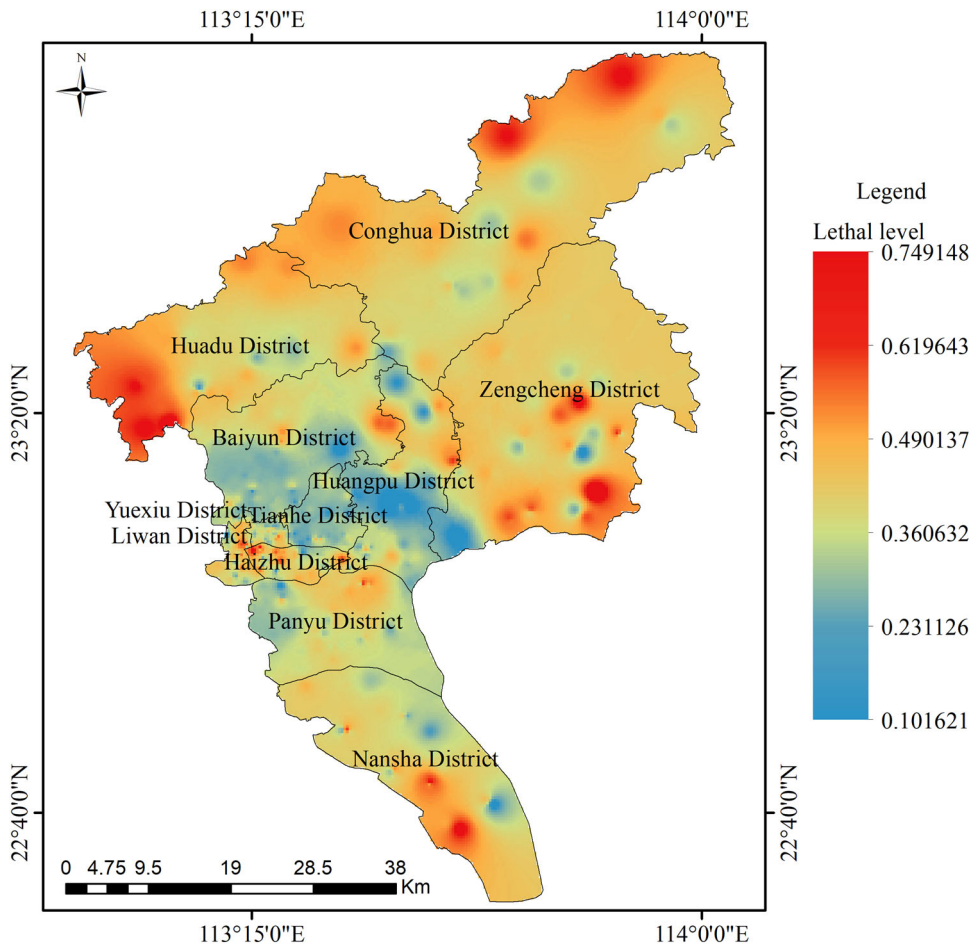


Figure 5. Distribution of the lethal level in Guangzhou City.

with a complete beam and column system, the beam and column diameter are generally above 50 cm, the foundation is also a standard concrete foundation, and the building height is generally above 5 storey. At the same time, there is another obvious feature of frame structure building in Guangzhou. There are a large number of self-built buildings built in the form of frame structures, but there are obvious differences in quality, beam and column diameter, etc.

The field investigation results reveal another obvious feature of the buildings in Guangzhou: the architectural form and quality of the buildings are greatly affected by the level of economic development. Many self-built brick-concrete structures are not equipped with structural columns; the first-floor roof is mainly a prefabricated slab, but with an improvement in the economic level, the second floor (added at a later stage) commonly has a cast-in-place roof, which is another reason for the high lethal level.

There are numerous urban villages in the urban area of Guangzhou. The buildings in this urban area were generally built in the 1970s and 1990s, and the structural



measures of the buildings are poor; these buildings are not equipped with ring beams or structural columns, and the building height is generally more than 2 stories. Furthermore, the spacing between buildings is small (generally within 2 m), especially in the central area where there are many buildings exceeding 5 floors and the layout of the buildings is messy. Notably, many hanging objects can be observed on the exterior walls of buildings, and there are a large number of nonstructural and accessory facilities such as air-conditioning units and billboards.

In contrast, the buildings in the rural areas of Guangzhou show different characteristics. These buildings are mainly brick-concrete structures, and there are also civil and brick-wood structures. The walls are mostly 18 cm thick, and the wall bonding material is generally lime mortar or loess mud. The foundation is shallow, generally a gravel foundation approximately 80–100 cm deep.

### *Lethal level distribution in Guangzhou*

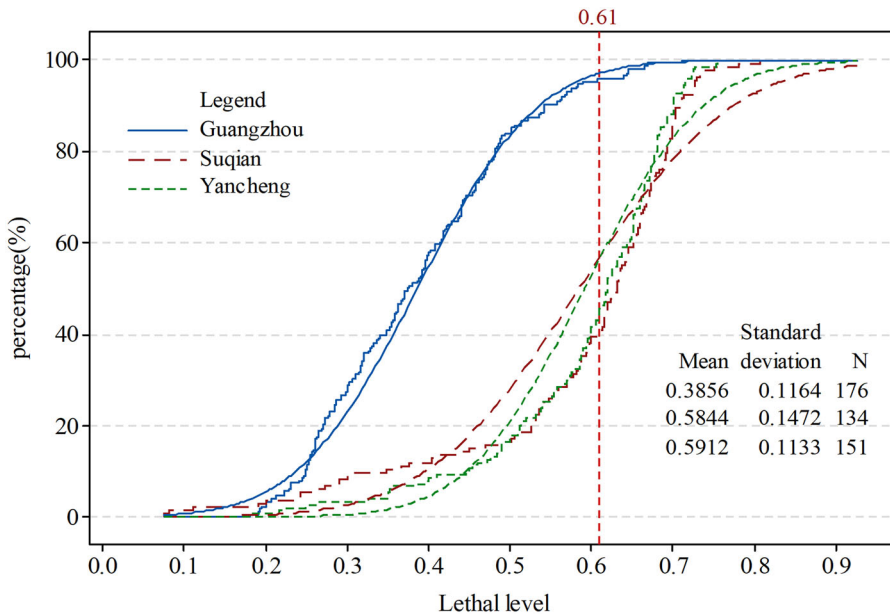
As shown in Figure 5, the earthquake resistance of the buildings throughout Guangzhou is good, with values generally below 0.5. The lethal level distribution in Guangzhou has obvious geographic characteristics, showing an increasing trend from the central area outward to the surrounding areas. The 3 urban expansion areas of Baiyun District, Tianhe District and Huangpu District have the best earthquake-resistant fortifications and thus the lowest lethal levels.

In the 5 satellite urban areas of Panyu District, Huadu District, Nansha District, Zengcheng District, and Conghua District, the regional earthquake resistance is adequate, and the lethal level is low, generally below 0.35. In contrast, in the 3 older urban areas of Liwan District, Yuexiu District, and Haizhu District, the lethal level is high, generally 0.5 or more, and the earthquake resistance of the buildings therein is weak.

The areas with good earthquake resistance are concentrated in Baiyun District, Huangpu District and Tianhe District, while the earthquake resistance of buildings in the central areas of cities such as Yuexiu District, Liwan District and Haizhu District is poor. The main reason for this discrepancy is that although there is a large number of buildings with good construction quality (such as reinforced concrete structures) in the central areas of cities, there are also large numbers of old brick-wood and brick-concrete structures, most of which were built from the 1970s to the 1990s. The building height is generally approximately 1–3 floors, the walls are mainly empty bucket walls, the thickness of which is generally 18 cm, and the roofs are mostly cast-in-place roofs, but the roof thickness is generally approximately 10 cm.

### *Comparative analysis of the lethal levels in the 3 cities*

As shown in Figure 6, the lethal level distribution characteristics of the towns among the 3 cities are obvious. The average lethal level in Guangzhou is 0.3856, and the standard deviation is 0.1146; the average lethal level in Suqian is 0.5844, and the standard deviation is 0.1472; and the average lethal level in Yancheng is 0.5912, and the standard deviation is 0.1133.



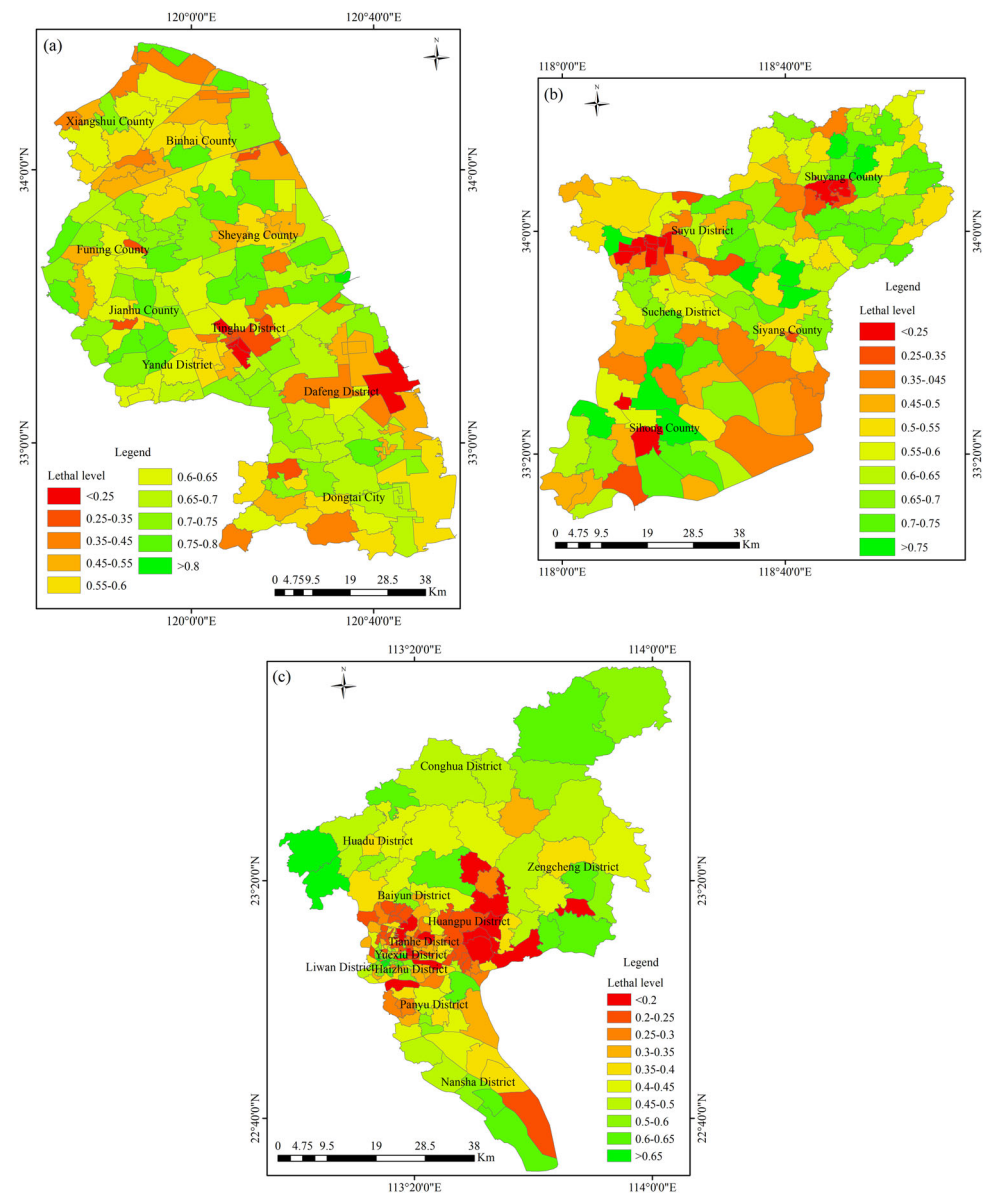
**Figure 6.** The lethal level distribution characteristics of the towns among the 3 cities.

The lethal levels of Yancheng and Suqian (which are in the same province) are close, suggesting that the lethal levels of different cities in the same province may be within the same range (for example, Yancheng city and Suqian city have similar levels). Although the average lethal level of Yancheng and Suqian are relatively similar, there are still certain differences. In the range where the lethal level is below 0.61, the lethal level of each township in Suqian is higher than that of each township in Yancheng, however, within the range where the lethal level is above 0.61, the lethal level of each township in Suqian is lower than that of each township in Yancheng.

At the same time, there are significant differences in the lethal level between different cities in the same region; the lethal level of the towns in Guangzhou are concentrated in the range below 0.61, which proportion is about 90%, however, the lethal levels of the towns in Yancheng and Suqian are concentrated in the range below 0.61, which proportion is about 60%, there is a more obvious difference between the two, the lethal level in Guangzhou is much lower than those in Yancheng and Suqian, and the distributions characteristics of the lethal level and economic level is very obvious and positively correlated. For example, Guangzhou and Yancheng are both located in the eastern area, and the types of building structures are similar; however, due to differences in the construction materials, construction age, construction quality, and construction methods, there are variations in the regional lethal level.

### *Distribution of the lethal level at the township level*

As shown in Figure 7, according to the distribution of the lethal level at the town level, the 3 cities exhibit unique characteristics. First, in Yancheng city, the areas with low lethal levels are mainly concentrated in urban areas, such as the streets and towns



**Figure 7.** Town-unit distributions of the lethal level in the 3 cities.

in Tinghu District, while the lethal levels in most nonurban towns and villages are generally high (exceeding 0.5). In addition, Suqian city presents distribution characteristics similar to those of Yancheng city: the lethal level is generally above 0.5, the towns with low lethal levels are concentrated in urban areas, and the economic development of towns has occurred in recent years. However, the lethal level distribution at the township level in Guangzhou presents completely different characteristics. The lethal level in the urban area of Guangzhou is high, generally exceeding 0.45, while the towns and villages with low lethal levels are concentrated in 3 new urban areas, namely, Huangpu District, Tianhe District and Baiyun District, in which the lethal

level is generally below 0.4, while the lethal levels in the towns far from the urban area are similar to those in Yancheng and Suqian.

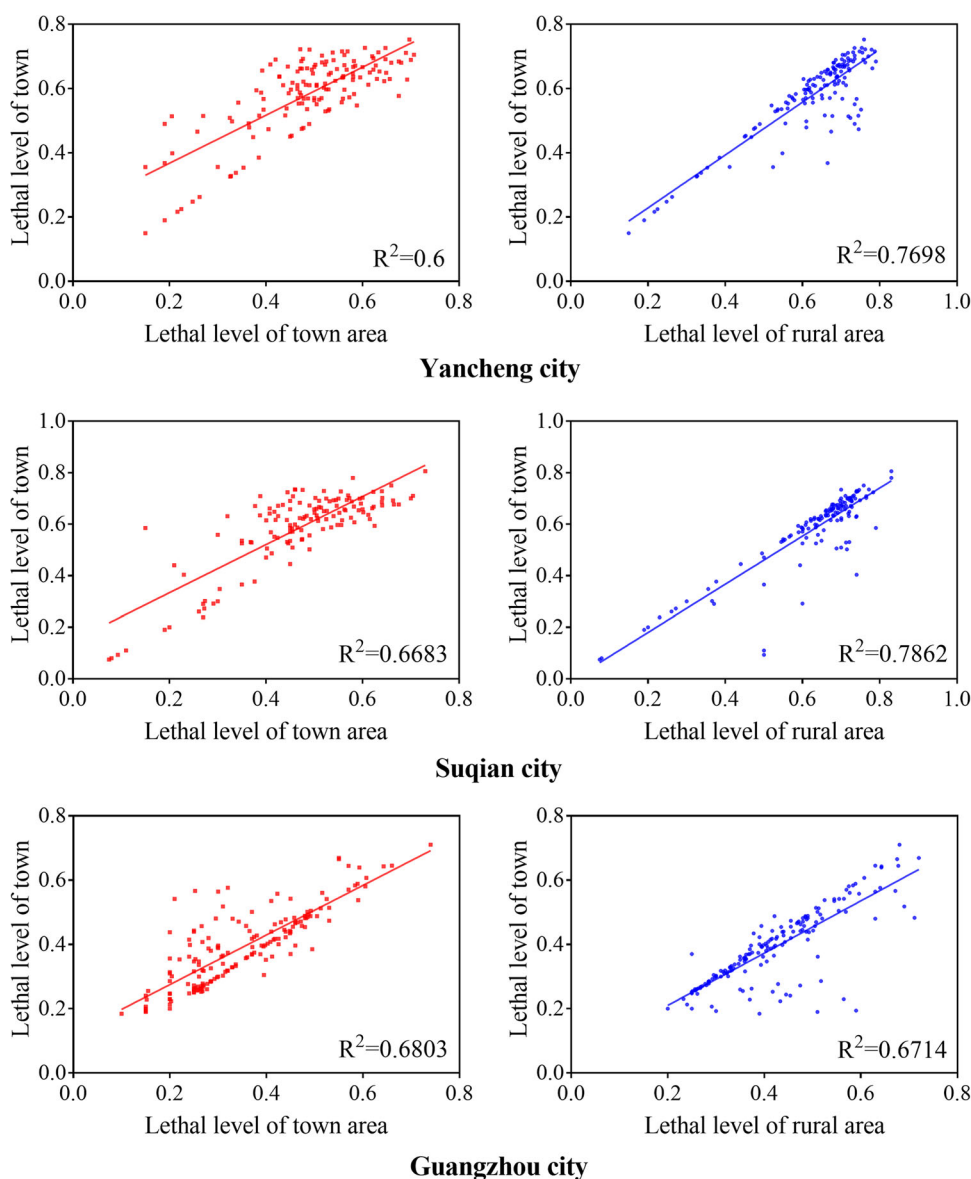
According to the lethal level of each town in the 3 cities, the lethal levels of town areas and rural areas have obvious distribution characteristics, the lethal level of town areas in each town in Guangzhou city is relatively average, and the level of town areas in some towns is higher than the average level of the whole town, correspondingly, there are more rural areas where the lethal level is lower than the average level; the level of the town areas in each town in Yancheng city showed similar characteristics to that of Guangzhou, however, the lethal level of the rural areas of Yancheng city shows obvious differences, basically, the lethal level of most rural areas is much higher than the average level of the town, the distribution characteristics of the lethal level in the town areas and rural areas of each town in Suqian city are highly similar to those in Yancheng city. Through a fitting analysis of the lethal levels in the town areas and rural areas of 3 cities and the average value of each town, it is found that the fitting results are relatively good, the  $R^2$  results are all above 0.6, the fitting result of the town area of Guangzhou is better than that of the rural area, the fitting results of Yancheng city and Suqian city show that the rural area is better than the town area, it reflects the basic characteristics of the distribution of lethal level in each town of each city, as shown in [Figure 8](#).

### *Distributions of the peak ground acceleration in the 3 cities*

The seismic peak ground acceleration of each township in study area is determined according to the fifth-generation seismic ground motion parameters zonation map of China (SAMR, 2015), (The basis ground motion corresponding to the probability of exceedance 10% in 50 years). The PSHA method was used in the compilation of the seismic ground motion parameters zonation map, at the same time, a probabilistic seismic hazard analysis method (PSHA) was constructed based on a hierarchical model of the potential source area and a seismic activity model that satisfies the expression of spatial distribution inhomogeneity. In this paper, the seismic hazard is expressed by the seismic peak ground acceleration (the basis for determining seismic intensity) which is the acceleration index of ground motion during earthquakes.

As shown in [Figure 9\(a–c\)](#), based on the basic peak ground acceleration (PGA) of the Class II sites in cities and towns across the country, the PGA distribution in each city is obtained. The PGA distribution in Yancheng decreases from east to west. The PGA distribution in Suqian also displays an obvious geographical trend that increases trend from east to west, that in Guangzhou shows a north-south distribution with an increasing trend from north to south. The geographical PGA distributions in the 3 cities are obviously unique.

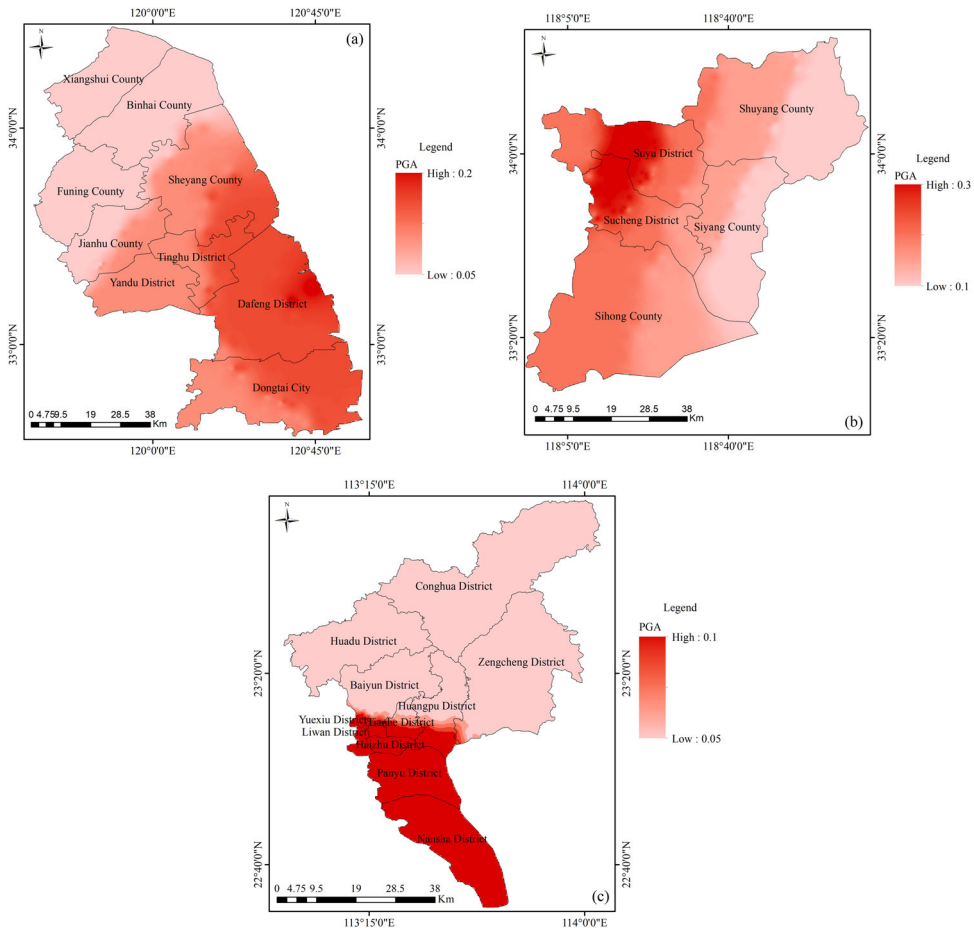
As shown in [Figure 10a](#), the comparative analysis of the lethal levels and PGA distribution among the towns in Yancheng city reveals that the lethal level varies considerably among the towns (from 0.2 to 0.7). In contrast, the PGA does not change much in each town; it is generally divided into four levels: 0.05 g, 0.1 g, 0.15 g, and 0.2 g. The proportion of buildings at each level is quite different, with most occurring at levels of 0.1 g and 0.15 g, but different towns and villages at the same PGA level have different levels of lethality. That is, even at the same PGA level, due to



**Figure 8.** Distribution characteristics of lethal level in different regions of each town in the 3 cities.

differences in the lethal level, the damage the buildings may actually suffer differs. For example, the PGA of two towns is 0.1 g, but the lethal level of one town is close to 0.7, while that of the other is close to 0.2 g. Hence, there are tremendous differences in the lethal level.

As shown in [Figure 10b](#), the comparative analysis of the lethal levels and PGA distribution among the towns in Suqian city suggests that the PGA distributions of different towns may be the same, but the lethal level differs throughout the region. The PGA is generally divided into 4 numerical levels of 0.1 g, 0.15 g, 0.2 g, and 0.3 g. There is little difference in the proportion of buildings among these levels. However, different towns at the same PGA level have different levels of lethality; that is, even



**Figure 9.** Distributions of the PGA in the 3 cities.

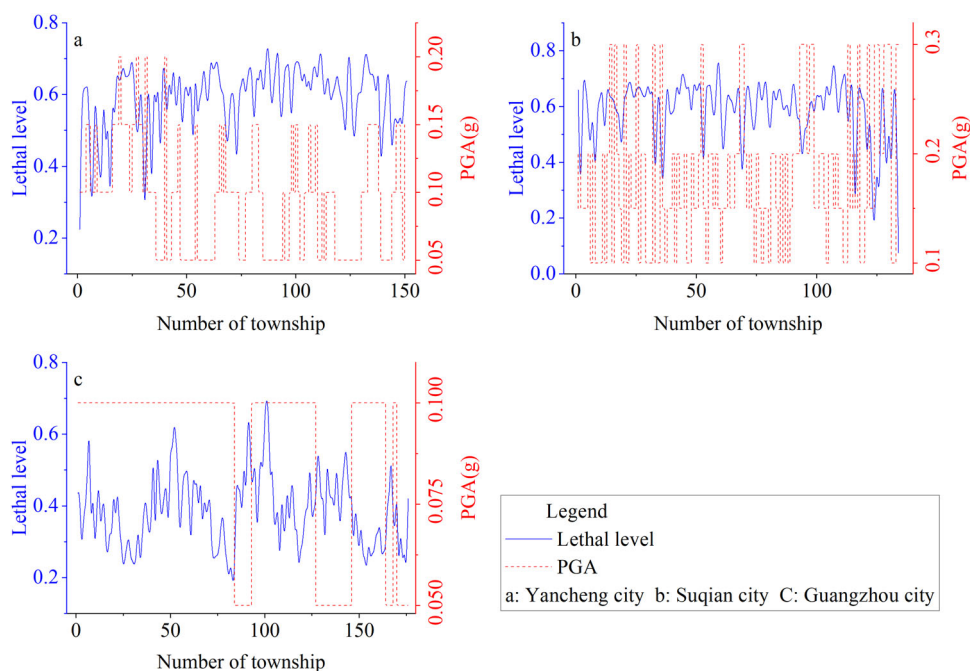
under the same PGA level, due to the differences in their lethal levels, the level of damage those buildings may suffer is actually different.

As shown in [Figure 10c](#), the comparative analysis of the lethal levels and PGA distribution among the towns in Guangzhou reveals that the lethal level varies considerably in each town (from 0.1 to 0.7), whereas there is little variation in the PGA, generally divided into 2 levels (0.05 g and 0.1 g). The PGA distribution at each level indicates little difference in the proportion of buildings. However, different towns at the same PGA level display varying levels of lethality; that is, even under the same PGA level, the lethal levels are different.

### **Earthquake disaster risk results**

Based on the lethal levels, the numbers of permanent residents, and the PGA values at the different sites, the earthquake disaster risk results were obtained, revealing the obvious characteristics of the earthquake risk distributions in the 3 cities. Among these cities, the areas with high earthquake risk in Yancheng are mainly distributed





**Figure 10.** Comparison between the lethal level and PGA of townships in 3 cities.

in Tinghu District, Sheyang County, northwestern Dafeng District, and the south-western area of Dongtai city. In addition, although there are other areas with high levels of earthquake risk, their overall risk level is lower than that of other districts and counties. Specifically, the areas with high earthquake disaster risk levels in Yancheng mainly include the following, as shown in Figure 11: Dayang street and Wuxing street in Tinghu District; Xindu street and Longgang street in Yandu District; Shanggang town in Jianhu County; Xingou town and Batan town in Funing County; Dongkan town in Binhai County; Yunhe town in Xiangshui County; Linhai town, Huangshagang town and Xintan town in Sheyang County; Xinfeng town in Dafeng District; and Qionggang town in Dongtai city and the surrounding areas.

The earthquake disaster risk levels of Suqian city are lower than those of Yancheng city. Generally, the areas with relatively high earthquake disaster risk levels in Suqian city are mainly concentrated in Sucheng District and Suyu District. Specifically, the areas with high earthquake disaster risk levels mainly include the following, as shown in Figure 12: Wanpi town, Machang town, and Zhouji town in Shuyang County; Zhongxing town and Aiyuan town in Siyang County; Qingyang town, Shuanggou town and Longji town in Sihong County; Xiaodian town and Shunhe town in Suyu District; and Shuangzhuang town, Sankeshu town, Tuyuan town, Cangji town and Zhenglou town in Sucheng District.

Compared with those of Yancheng city and Suqian city, the earthquake disaster risk levels of Guangzhou city are significantly different. The risk level of nonurban areas in Guangzhou city is significantly lower than that of urban areas, and the high earthquake disaster risk levels are concentrated primarily in the urban areas of Liwan District, Yuexiu District, Haizhu District and Panyu District. In addition, the risk levels of some



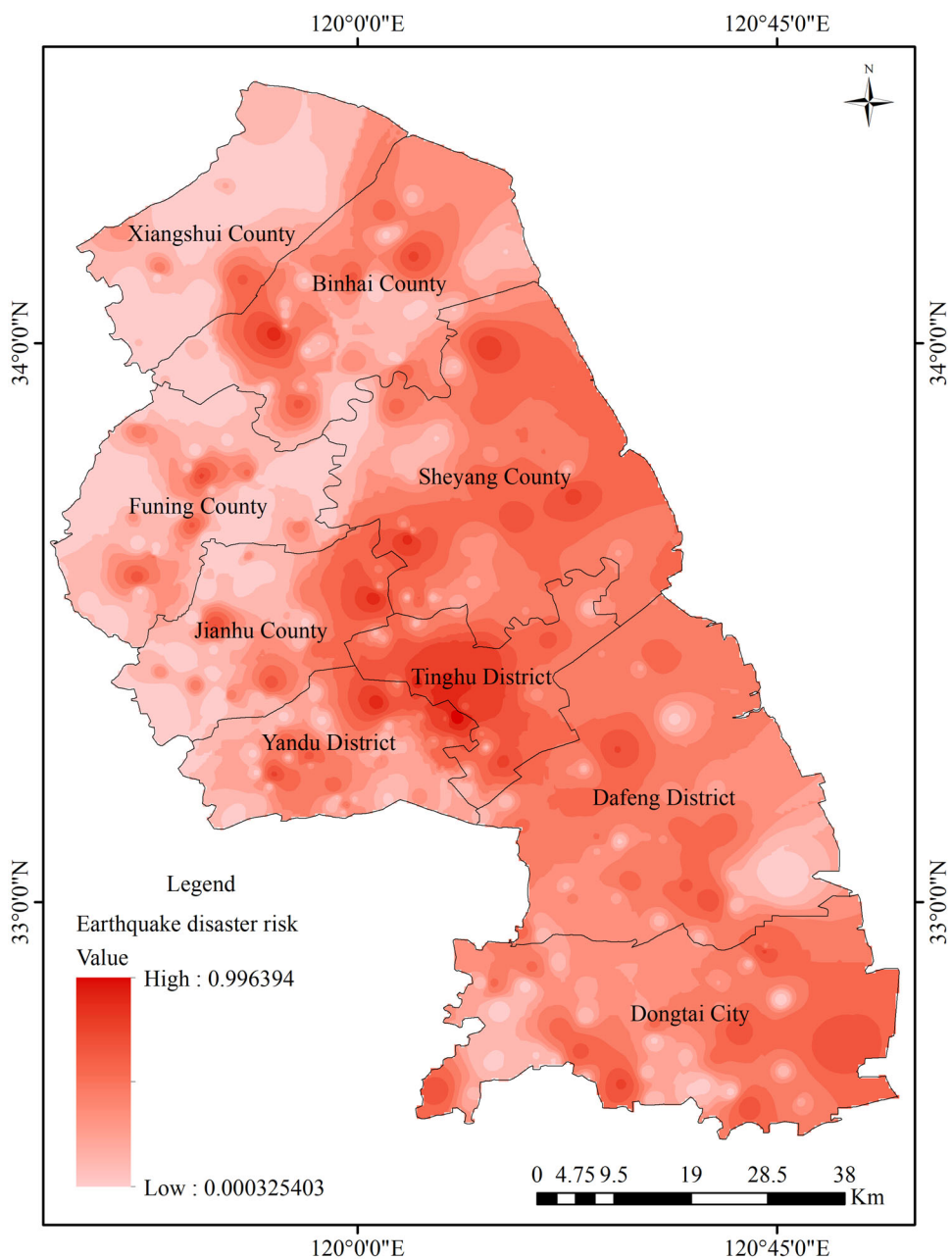
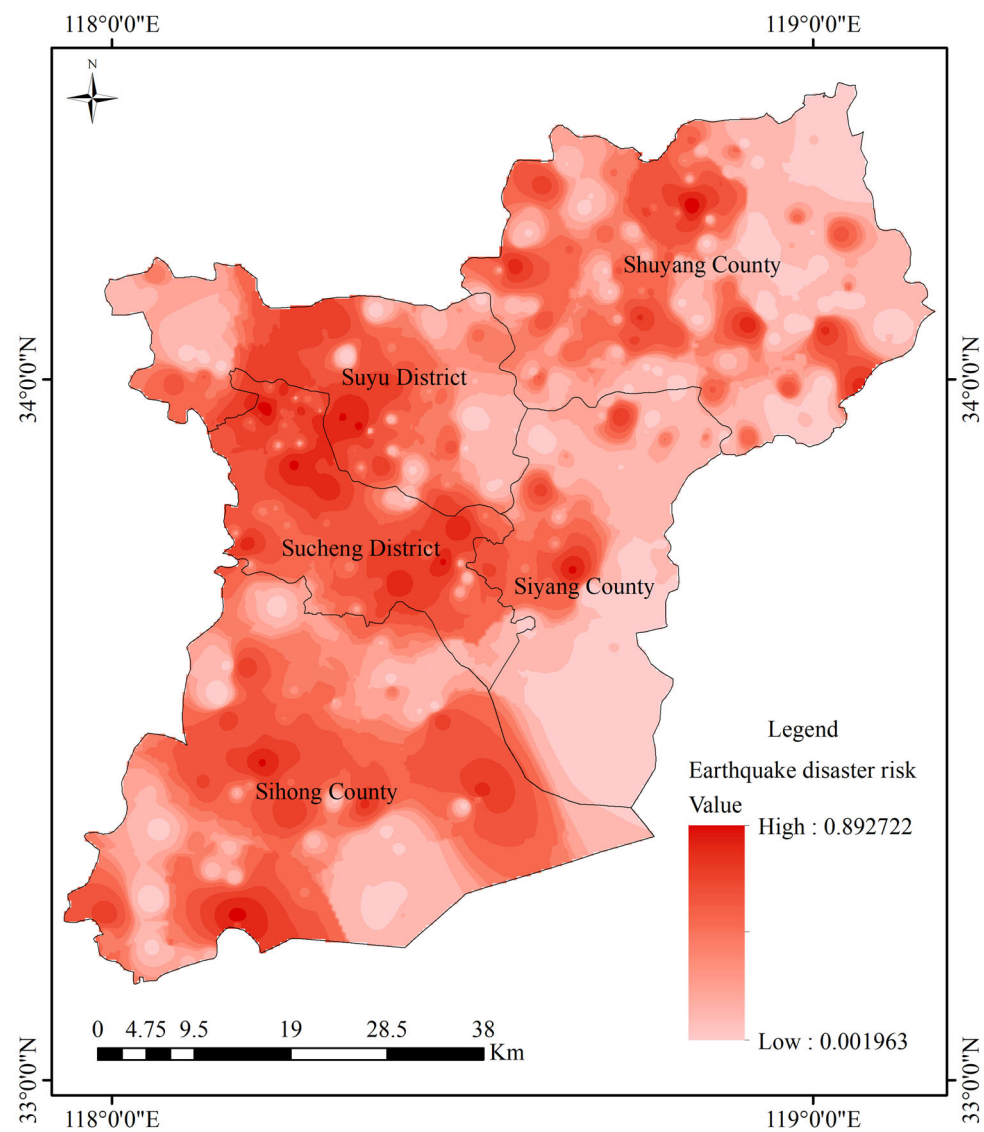


Figure 11. Earthquake disaster risk distribution map of Yancheng city.

rural areas in Baiyun District and Huangpu District are high, including those in Conghua District, Wenquan town, and Paitan town in Zengcheng District; the junction area of Zhengguo town, Xiaolou town, Licheng Street and Zengjiang Street in Tanbu town and Xinhua Street in Huadu District; Jinsha Street and Junhe Street in Baiyun District; Shijing Street and Tangjing Street and Hailong Street and Zhongnan Street in Liwan District; Tangxia Street and Qianjin Street in Tianhe District; Ruibao Street and



**Figure 12.** Earthquake disaster risk distribution map of Suqian city.

Chigang Street in Haizhu District; Lilian Street and Huangpu Street in Huangpu District; Panyu District; Nancun Town and Shilou Town in Nansha District; Dongyong Town and Lanhe Town in Nansha District, as shown in [Figure 13](#).

### Discussion

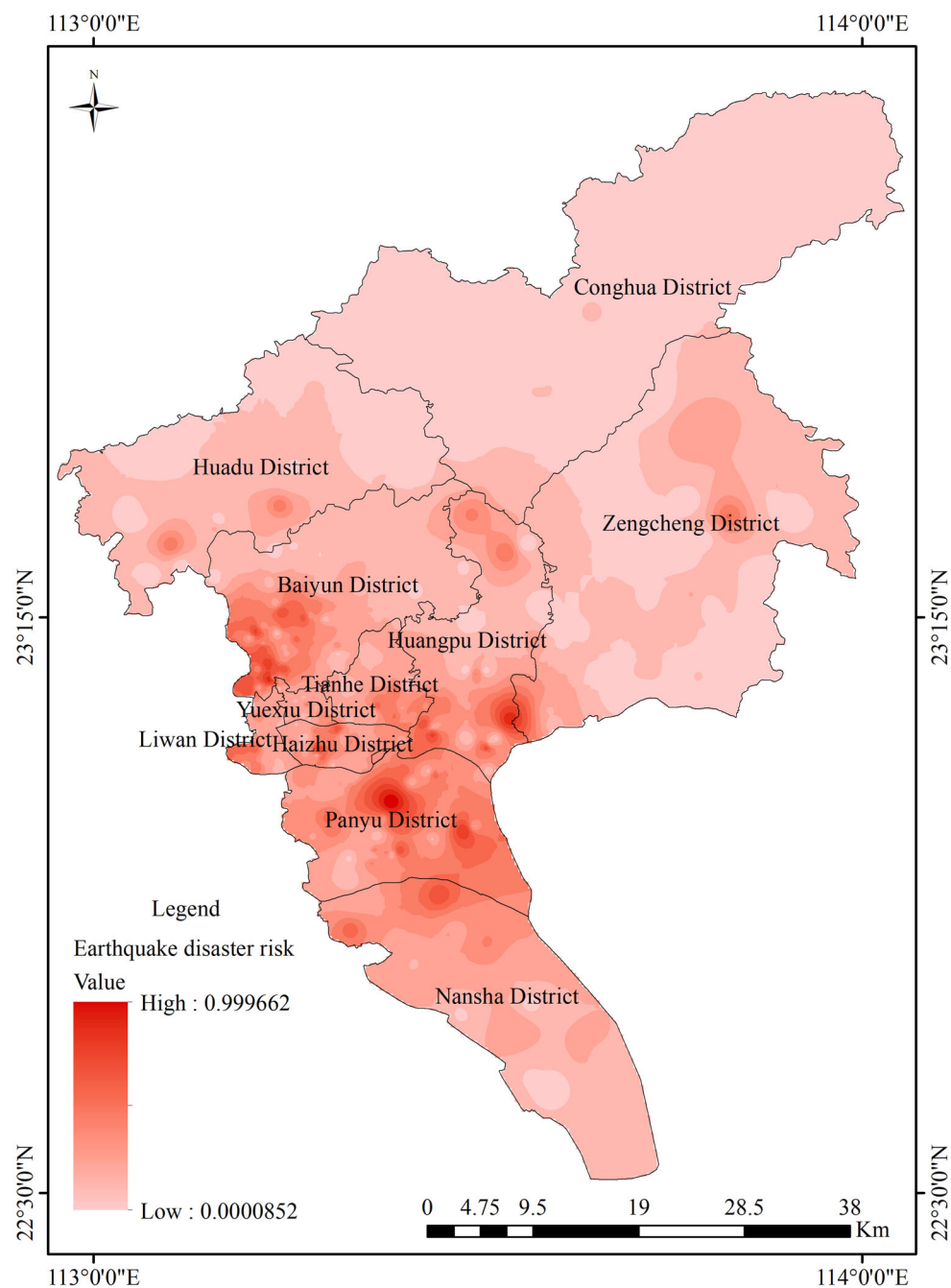
Field surveys in different cities throughout eastern China reveal that the building types in each city are basically similar, mainly including reinforced concrete structures, brick-concrete structures, brick-wood structures and civil structures, but they are affected by varying factors such as the level of economic development; moreover, there are obvious differences in the construction methods and construction quality

among buildings of the same types, such as brick-concrete structures and brick-wood structures. There are also obvious differences in the quality and form of two types of buildings among the different cities. Brick-concrete structures may include fortified brick-concrete (with structural measures such as structural columns and ring beams) and unfortified brick-concrete (with ring beams and no structural columns or no ring beams and no structural columns); for example, in Yancheng city and Suqian city, the brick-concrete structures are generally equipped with ring beams but no structural columns, and the roofs are mainly prefabricated. At the same time, there is a certain proportion of brick-concrete structures with ring beams and structural columns, and the roofs are cast in place. However, among the brick-concrete structures, the proportion of unfortified brick-concrete structures is large. The field survey results are more consistent with the results of related literature, most of the buildings in Suqian City have not been fortified against earthquakes or the fortification intensity does not meet the requirements of the current regulations. At the same time, there are a large area of privately built houses in the urban-rural junction. Due to the lack of seismic measures, their seismic capacity is poor and their vulnerability is high (Yang et al. 2017).

While the buildings in Guangzhou show obvious differences, the brick-concrete structures generally have ring beams and structural columns with cast-in-place roofs. At the same time, there are many unfortified brick-concrete structures in the urban villages and rural areas in Guangzhou; these structures have no ring beams or structural columns, but the roofs are cast in place, and the thickness is generally between 8 and 10 cm, which is obviously different from the same type of buildings in Yancheng and Suqian.

On the other hand, the brick-wood structures are clearly different among the 3 cities. The brick-wood structures in Yancheng and Suqian include 2 main types: the wall thickness is typically either 24 cm or 18 cm, and the bonding material of the wall is mainly lime mortar. In contrast, the thickness of the walls in the brick-wood structures in Guangzhou is generally 24 cm, but these buildings are old, and the bonding material is generally loess mud. In other words, even for the same building types in different cities, there are obvious differences in the wall properties and building materials, resulting in significant differences among the lethal levels of the same building type in different cities. Therefore, if an earthquake disaster risk analysis is carried out based only on the vulnerability analysis results of the building type, the difference between the same building type will be ignored, as a result, the assessment results of casualties and economic losses based on vulnerability may be more restrictive (Hassaballa et al. 2017; Mulargia et al. 2017; Dabbeek and Silva 2020).

According to the results of the field surveys in the three cities, the lethal level in each city varies substantially, the range of lethal levels in Yancheng is 0.15–0.83, that in Suqian is 0.07–0.82, and that in Guangzhou is 0.1–0.74. Moreover, the lower limit of the lethal level is the smallest in Suqian city, followed by Guangzhou, and Yancheng has the highest lower limit; however, Guangzhou has the smallest upper limit of the lethal level, followed by Suqian city, and Yancheng city has the highest. Although Guangzhou's level of economic development is higher than that of both Yancheng city and Suqian city, the lethal levels at some survey points in Suqian are



**Figure 13.** Earthquake disaster risk distribution map of Guangzhou city.

lower than those at some survey points in Guangzhou. Hence, the distribution of the lethal level of a city is generally positively correlated with the level of economic development, but this correlation is not absolute; in other words, the lower limit of the lethal level of a city with a high economic level may be smaller than that in a city with a poor economic level. The average lethal level in Guangzhou is 0.3856, the

average lethal level in Suqian is 0.5844, and the average lethal level in Yancheng is 0.5912. The total difference is 0.1133, and the lethal level of Guangzhou city is much lower than that of both Yancheng city and Suqian city, which (although they are located in the same province) have high average lethal levels. At the same time, the distribution characteristics of the lethal level of each town in the 3 cities are also obvious. The lethal level of each district and county in the urban area of Yancheng is generally lower than that in the nonurban regions which showing a clear correlation with the level of economic development.

For Yancheng city, the lethal level of the urban areas of Tinghu District and Yandu District is lower. The areas with a low lethal level in Dafeng District are mainly located in the seat of the government and economic development zones. The overall lethal level in Dongtai city is average, and the areas with a low lethal level are mainly located in the western development zone. In addition, some towns and villages in Sheyang County, Funing County, Jianhu County and Binhai County and other regions have obviously low lethal levels; these regions are concentrated in districts, counties and towns, while Xiangshui County has a weak level of economic development, and the areas with lower lethal levels are mainly located in economically developed towns.

For Suqian city, the distribution of lethal levels has notable characteristics, the overall lethal level of Sucheng District and Suyu District (especially in the urban areas) is relatively low, much lower than the levels of the other towns. Among the other districts and counties, such as Sihong County, Siyang County, and Shuyang County, the lethal levels in town areas are high. In contrast, the lethal levels in rural areas are low. This distribution is quite different from that in Yancheng.

For Guangzhou city, the town-unit lethal level distribution displays obvious characteristics that are different from those of Yancheng and Suqian. First, the average lethal level of Guangzhou is much lower than that in the other two cities. The township-scale distribution of the lethal level also exhibits unique features. The lethal levels of each township in Huadu District, Conghua District, Zengcheng District, Panyu District and other districts and counties are moderate and do not vary much. Compared with other districts and counties, Huangpu District, Tianhe District and Baiyun District have generally lower lethal levels. The main reason is that these 3 districts are new urban areas; due to economic development and growth policies, most of the buildings in these areas are newly constructed or refurbished. These reconstruction efforts have lowered the lethal level, whose overall seismic capacity is higher than that of other townships. Another major feature of Guangzhou pertains to the 3 districts located in the urban area: Yuexiu District, Liwan District, and Haizhu District, the lethal levels are generally high, the mainly reason is there are many urban villages, and the main buildings in these villages are brick-wood structures and brick-concrete structures, most of them have no ring beams or structural columns, there are generally more than 2 stories, the construction quality is poor, the buildings are densely distributed, the planning scheme is unreasonable, and the roads are narrow, as shown in Table 4 of the road characteristics. As a consequence, the lethal levels in the urban areas of Guangzhou are higher than those in nonurban towns and villages.

The field surveys of the 3 cities in eastern China indicate that the distributions of both the regional lethal level and the earthquake disaster risk level have remarkable features.



For Yancheng and Suqian in the same province, there is a clear correlation between the distributions of the earthquake disaster risk and lethal levels. The higher the lethal level is, the higher the earthquake disaster risk. However, there are particularly obvious discrepancies with the distribution of the earthquake disaster risk in Guangzhou city, which shows obvious regional characteristics. The earthquake disaster risk for these 3 cities in eastern China show that under normal circumstances, the earthquake disaster risk in urban areas is lower than that in nonurban areas, but this relationship is not absolute.

Based on these results, the differences in the earthquake disaster risk level among the three cities are apparent. There are two reasons for the high earthquake disaster risk in Yancheng. First, the buildings in the urban areas (such as Tinghu District) are mainly brick-concrete structures, but due to the limited level of economic development, the buildings are generally old, and as a result, many of the brick-concrete structures in the urban areas are unfortified buildings or are old-fashioned structures of poor construction quality (Wang et al. 2008a, 2008b). Furthermore, there are obvious disparities among some townships in the urban areas. Although the buildings in the towns are mainly brick-concrete structures, these buildings are generally fortified brick-concrete structures with ring beams and structural columns. Another main reason is the resident population, especially the permanent population, as the population density is higher than that of other towns.

The lethal level of Suqian city is similar to that of Yancheng city. Nevertheless, the earthquake disaster risk levels are quite different; the reason for this is the disparity in the PGA distributions of the 2 cities. Under the same lethal level, the PGA of Suqian is smaller than that of Yancheng. As a result, the earthquake disaster risk of Suqian city is lower than that of Yancheng city. Another main feature of the earthquake disaster risk in Suqian is that there are few high-risk areas, but it shows obvious regionality, with the risk level in rural areas being lower than that in the towns. On the other hand, the types of brick-concrete structures in the town areas are quite different in terms of their construction quality and fortification conditions, and the age of the structure still has a considerable influence.

Guangzhou city exhibits obvious differences. In general, earthquakes are mainly concentrated on the edge of the delta, which is strong in the west and weak in the east, and strong in the north and weak in the south (Guo et al. 2008; Zhang 2014), the reason for the high risk levels in Baiyun District and Huangpu District is mainly due to the existence of many unfortified brick-concrete structures and old brick-wood structures in rural areas. In Liwan District, Yuexiu District, Haizhu District and Panyu District, the first reason for the high levels of risk is the large number of urban villages in the area with dense, messy layouts of buildings, narrow roads, and a much higher population density than other areas; second main reason is the poor construction quality of buildings, there is a large number of unfortified structures; in particular, the brick-concrete structures are mainly brick-concrete structures without structural columns and more than two stories, the third main reason is the high population density, which is much higher than that of other regions or other cities, and is showing an aging trend (Xie and Ning 2006; Lan and Huang 2012; Lin et al. 2020).

In fact, the lethal level of an area is mainly affected by the type and number of buildings, the geographical environment, and traffic and road conditions, and also

affected by the number of permanent residents. That is, even if two cities or towns have the same building types and similar building proportions, their corresponding earthquake disaster risk is not necessarily the same.

## Conclusion

Analyses of the lethal levels and earthquake disaster risk distributions in 3 cities in eastern China demonstrate that the types of buildings in different provinces are basically the same, but the lethal levels of the same buildings in different provinces still diverge. As a result, the lethal level varies considerably even in different cities within the same area. Therefore, the lethal levels of different areas can better reflect specific regions. The earthquake disaster risk results obtained based on the regional lethal levels reflect the ability of an earthquake in the area to cause casualties and considers the number of permanent residents in the area; hence, the resulting risk distribution can reflect the weak links in the area. Moreover, emergency preparedness and rescue plans can be targeted based on these results.

On the other hand, since the lethal level actually represents the probability of death after an earthquake in an area, in this article, the earthquake disaster risk level obtained based on the lethal level is actually a measure of the relative magnitude of the earthquake disaster risk. As earthquake casualties are mainly affected by the earthquake intensity and subsequent mortality, variations in the lethal level and different intensities indicate that the corresponding probability of death may diverge among areas with different levels of lethality. The proposed method takes the lethal level as a limiting condition and constructs a functional relationship to assess casualties based on the earthquake intensity and mortality rate. Therefore, if it is possible to obtain the lethal level of a region through field investigations during an aseismic period, based on the survey results, it is possible to carry out high-precision quantitative research on the risk of earthquake casualties and then obtain the earthquake disaster risk distribution with high precision based on the lethal level.

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## Data availability statement

The data that support the findings of this study are available from the corresponding author, Chaoxu Xia, upon reasonable request.

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