Risk assessment of people trapped in earthquake disasters based on a single building: a case study in Xichang city, Sichuan Province, China

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ABSTRACT

Strengthening the study of trapped personnel distribution in an earthquake not only ensures the efficiency and orderliness of earthquake rescue but also maximizes the survival probability of trapped people and reduces casualties. Through distinguishing the use functions of buildings, this study constructed an assessment model of people trapped in a collapsed single building due to an earthquake and evaluated the risk of individuals trapped in Xichang area, China. The results showed that the risk level of people trapped in collapsed buildings in Xichang area is high. Under the influence of seismic intensity $I$, the proportion of people trapped in collapsed buildings has reached approximately 1–2% of the total regional population. The risk level of trapped people in the daytime and at nighttime caused by the same earthquake scenario is significantly different. The number of potentially trapped people at night is nearly two times greater than that during the day. The low seismic performance of buildings is the most important factor causing the high risk of people trapped. The use function of buildings also has an important effect on the risk assessment of the trapped population distribution. Some suggestions are provided for the local risk reduction of people trapped in earthquakes.

1. Introduction

Earthquakes are the most unpredictable natural hazards. A quake occurs almost instantaneously, but the impact lasts for a long time and causes great human losses. One of the most feasible and effective strategies to reduce social and economic losses caused by earthquakes is to mitigate the vulnerability of society to seismic hazards based on an accurate and scientific risk assessment (Tantala et al. 2008). An estimation of the spatial distribution of casualties is essential to the entire postearthquake rescue operation (Feng et al. 2013). Following this estimation, emergency search and
rescue (ESAR) activities can be prioritized and rationally coordinated (Erdik et al. 2014).

Due to the importance of a casualty assessment, in recent decades, researchers worldwide have been trying to assess casualties at different regional scales by using various data and methods (FEMA (Federal Emergency Management Agency) 2003; Hancilar et al. 2010; Furukawa et al. 2010; CAPRA 2012; Shapira et al. 2015; Corbane et al. 2017; Robat Mili et al. 2018; Quagliarini et al. 2019; Pnevmatikos et al. 2020; Zlateski et al. 2020). For example, Badal et al. (2005) used a quantitative model to assess earthquake losses and damages, which includes a correlation between the earthquake magnitude and the number of lives lost. Using a backpropagation neural network method, Aghamohammadi et al. (2013) estimated human losses as a function of building damage during an earthquake. So and Spence (2013) employed a global casualty estimation model to measure shaking-induced casualties and building damage for global earthquake events. Huang et al. (2015) proposed a robust wavelet v-support vector machine earthquake casualty prediction model. Su et al. (2015) provided an integrated method for the large-scale estimation of seismic loss to buildings, by amalgamating remote sensing data and building-relevant local knowledge. Corbane et al. (2017) performed a seismic loss risk assessment at a pan-European level, depending on the open available datasets across the EU. Using the Earthquake Loss Estimation Routine model, Leousis and Pnevmatikos (2018) and Pnevmatikos et al. (2020) assessed the seismic losses for various seismic scenarios in Greece. Most recently, Quagliarini et al. (2021) proposed a holistic framework to support the risk assessment and emergency plan actions at the Historic Built Environment scale. As a whole, currently available earthquake casualty assessment approaches can be classified into three categories: empirical, semiempirical, and analytical. The advantages and disadvantages of each approach have been discussed in previous work (Nazari 2018; Wei et al. 2015). The semiempirical approach is typically more effective in developing countries such as China, due to their sufficient historical earthquake data to estimate collapse fragility functions and calculate fatalities (Jaiswal et al. 2011; Spence and So 2009; Yuan et al. 2019).

It is now widely recognized that the number of deaths during an earthquake, is closely related to the quantity of buildings that fully or partially collapse (Bai 2006; Lu et al. 2003; Ma and Xie 2000a; So and Spence 2013; Yin 1996). The collapse of building structures is the most common cause for people to be trapped during earthquakes (Marano et al. 2010; Sun and Zhang 2012; Wang et al. 2009; Wei et al. 2017a). Rapidly assessing the location and number of people trapped in damaged buildings, is one of the important ways to improve the efficiency of postdisaster emergency rescue and reduce casualties in an area immediately following an earthquake (Erdik et al. 2014; Wei et al. 2017b).

However, earthquakes can potentially occur at any time of day. In a densely populated urban area, the distribution of individuals depends on the time of day as a consequence of daily human routines (Ara 2014). The population distribution is very different during the daytime as opposed to the nighttime (Cheng 1993; Freire 2010; Ma and Xie 2000a). The risk of casualties varies significantly between night and day when an earthquake occurs (Alexander 1996; Ara 2014). Compared with an
earthquake in the daytime, night earthquakes will increase the number of casualties (Park et al. 2016). Especially from 23:00 to the next morning 5:00, people are sleeping and unable to rapidly respond to sudden earthquakes, resulting in an increase in casualties (Cheng 1993). Researchers have recognized that it is incredibly important to assess human losses throughout the temporal cycles of a day (Freire and Aubrecht 2012; Rivera et al. 2020). Factors including the time of day, presence of a holiday, occupancy type, weather, population structure, and the use function of the building all influence the population distribution and density and therefore also impact the number of casualties or people trapped in damaged buildings following an earthquake (Choi et al. 2019; De Lotto et al. 2019; Gao et al. 2014; Ma and Xie 2000a; Wei et al. 2017b). It is, therefore, necessary to take these factors into account to achieve a realistic assessment of human loss as a consequence of an earthquake.

Human effective response behaviors to disasters are also effective ways to reduce disaster risk and life losses (Shi et al. 2005; UN/ISDR 2005). Many works have investigated human behaviors in earthquakes, in both indoor and outdoor scenarios (Bernardini et al. 2016; Gu et al. 2016; Lambie et al. 2016; Yang et al. 2011), discussing the differences due to gender, ages and variations between real-world response and evacuation drills. The existing works showed that individuals’ safety in an earthquake highly depends on human emergency behaviors, especially in the first evacuation phases (Bernardini et al. 2019). According to statistical data of past earthquakes in mainland China, roughly 85% to 90% of victims who survived an earthquake disaster escaped through self and mutual rescue measures (Li 2006; Qu et al. 2010; Wang et al. 2012; Xiu 2004). The estimation of casualties due to an earthquake also needs to take into account human emergency response behaviors (Wald et al. 2011; Wei et al. 2017b). However, due to the limitation of available data, the variables related to the human response were rarely used in previous research on casualty estimations (Park et al. 2016; Wald et al. 2011).

China is one of the most earthquake-prone countries in the world. Since the 2008 Wenchuan earthquake, several destructive earthquakes have occurred in mainland China, which caused enormous casualties and economic losses. At present, most of the studies have focused on the assessment of the total casualties in an earthquake, but there have been few studies on the risk and distribution assessment of people trapped in earthquakes in China (Li 1987; Li et al. 2014; Ma and Xie 2000b; Wei et al. 2017a; Wu et al. 2011). In recent years, with the need for earthquake emergency rescue, some studies have paid attention to the estimation of people trapped in a collapsed building caused by an earthquake in China. For example, taking the 2008 Wenchuan earthquake as an example, Xiao et al. (2009) proposed a prediction model for the trapping rate based on the collapse rate of buildings and the occupancy rate. Yu et al. (2015) also provided a revised evaluation model of people trapped based on the trapping rate in the Wenchuan earthquake. By analyzing the main influencing factors, Wei et al. (2017b) proposed a grid-scale (1 km²) comprehensive assessment model to assess the risk of people trapped in collapsed buildings caused by earthquakes. Recently, taking Haidian District, Beijing, as an example, Yuan et al. (2019) modeled the fine-scale spatiotemporal pattern of earthquake casualties, by incorporating the estimation of population exposure and locally oriented damage
probability matrices. However, for ESAR operations during the early stages of a destructive earthquake, the available rescue time and disaster information are all very limited. The more detailed information on the people trapped, the clearer its guiding significance for ESAR and reasonable resource allocation, and the higher the efficiency and effectiveness of emergency relief. Building-level data can provide more detailed information on the people trapped than that from the assessment results at the grid scale (Ara 2014). Compared with building data at the grid scale, single building data could also provide specific use function information, with the exception of building structure information, which is a key factor affecting the population distribution in a day, especially for distinguishing the population exposure during the daytime and at nighttime. However, due to the limitation of obtaining the use function data of single buildings, this aspect is rarely considered in the current research on casualty estimations in China (Gao et al. 2014).

In view of the above mentioned, by constructing a single building-based risk assessment model of people trapped in an earthquake, this study evaluated the risk of individuals trapped related to a given earthquake scenario in Xichang city, Sichuan Province, China. The model constructed not only distinguishes the use function of buildings and identifies the difference of indoor population density in different functional buildings, but also considers the self-aid and mutual aid (SAMA) rate during an earthquake. It will allow to rapidly assess the risk distribution of people trapped in a collapsed single building; to evaluate the extent of the difference in the risk distribution of people trapped during the daytime and at nighttime under the same earthquake impact; and then, to provide better guidance for earthquake disaster preparedness and postdisaster ESAR operations.

2. Risk assessment model of people trapped in a collapsed single building

Existing work has established that the number of people trapped in collapsed buildings during earthquakes is decidedly dependent upon factors such as the scale of the earthquake hazard, building vulnerability, population exposure and human response (Coburn and Spence 2002; Wald et al. 2011; Wei et al. 2017b). Although the application of instrument parameters such as Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) has gradually increased in recent years, most estimations of earthquake disaster losses and building damage are based on the seismic intensity in China. The ground shaking intensity can more precisely indicate the damage following seismicity than the other parameters (SAC (Standardization Administration of China) 2008). Moreover, whether a building collapses during an earthquake is highly related to building vulnerability. Many factors, such as the building age, seismic protection code, structure type, anti-seismic measures, and occupancy types, affect the building vulnerability. At present, the earthquake damage index (EDI) and building damage probability matrix (DPM) are the two most commonly utilized methods to assess building vulnerability in China (Ma and Xie 2000b). Due to the concise and practical characteristics of the DPM, most studies have chosen DPM as the tool to
assess the vulnerability of buildings in China (Hu 2007; Sun and Zhang 2012; Zhang et al. 2007, 2010).

Population exposure is also a key component for the assessment of people trapped in damaged buildings due to an earthquake. As mentioned, population exposure data are strongly associated with temporal variations due to different human activities and mobility patterns during the daytime and nighttime (Freire 2010; Freire and Aubrecht 2012). Among them, the use function of buildings is one of the most important factors affecting population exposure. People will gather more in residential buildings at nighttime, while during the working day, they will gather more in office buildings. This will significantly affect the distribution of indoor population density in buildings at different time stages. Therefore, it is necessary to take the use function of buildings into account to achieve a realistic assessment of people trapped in an earthquake.

Additionally, the human response is also an indispensable component for the estimation of people trapped in a collapsed building due to an earthquake. Numerous societally dependent variables are related to the human response, including personal protection actions, building egress rates, rescue and emergency capabilities, etc. (Bernardini et al. 2019; Lambie et al. 2016; Wald et al. 2011). Among them, self-aid and mutual aid (SAMA) are an important emergency response behavior following an earthquake disaster (Bernardini et al. 2016; Wei et al. 2017b). Its significant role in improving postdisaster emergency rescue efficiency and reducing casualties has also been confirmed in previous destructive earthquakes in China (Qu et al. 2010; Wang et al. 2012; Wei et al. 2017b). Due to the complexity of human response behaviors and the limitation of available data, the SAMA rate can be considered as a comprehensive result of the human response following an earthquake.

Based on the above and our previous work, people trapped in a collapsed building due to an earthquake are defined as all of the deaths and injuries, as well as people who are not in immediate danger but cannot readily escape from a collapsed building in the study. Considering the ground shaking intensity, the number of buildings affected at a particular intensity, the structural damage rate, the use function of single buildings, the indoor population density at the time of an earthquake and the human response action, we therefore could construct a risk assessment model for the people trapped in a collapsed single building due to an earthquake as follows:

\[
TN_i = (1 - \delta) \times D_{ui} \times R_{ui}(t) \times (B_{si} \times L_s(I))
\]

(1)

where \(TN_i\) is the number of trapped people in a collapsed single building \(i\); \(D_{ui}\) is the average daily population density per building area (i.e. the daily accommodation population density (person/m\(^2\)), determining the population number carried by a certain type of buildings in urban daily activities) in the building \(i\) with the use function \(u\); \(R_{ui}(t)\) is the indoor occupancy rate (the proportion of the residents who are actually inside the building at time \(t\) of the earthquake) in a damaged building \(i\) with the use function \(u\); \(B_{si}\) is the total area (m\(^2\)) of the \(s\) structural-type single building \(i\) exposed to the earthquakes; \(L_s(I)\) represents the collapse rate of the \(s\) structural-type buildings at a particular shaking intensity \(I\), based on the Chinese seismic intensity scale (SAC (Standardization Administration of China) 2008); \(\delta\) is the SAMA rate (i.e.
the proportion of the people who can escape from a damaged building by themselves or through mutual aid) following the earthquake.

3. Model application in Xichang city

3.1. Study area

Xichang city is located on the eastern edge of the Hengduan Mountains and the hinterland of the Anninghe Plain, which is the second largest plain in Sichuan Province, China. It is the capital of Liangshan Yi Autonomous Prefecture in Sichuan Province (Figure 1). The altitude of Xichang city ranges from 1184 to 4152 m, and the terrain fluctuates greatly. The main terrain is the middle mountain, accounting for 78.9% of the total area. The valley plain, low mountain and high mountain areas account for 16.4%, 3.4% and 1.1% of the total area, respectively. At the end of 2018, the total household population of Xichang was 678.7 thousand. There are approximately 171.0 thousand ethnic minorities in the territory, accounting for 25.2% of the total population. By the end of 2018, the gross domestic product (GDP) was 779.357 million RMB. The income of urban and rural residents has increased steadily, and their living standards have been further improved. In 2018, the per capita disposable income of urban residents was 36819 RMB and that of rural residents was 17838 RMB (XSB (Xichang Statistics Bureau) 2019).

The Xichang area is located in the juncture area of two tectonic units: the Sichuan-Yunnan block and the South China block. Due to the collision and compression of the Sichuan-Yunnan block and South China block, the Mesozoic fault basin in the north, the Paleozoic depression in the east and the basement uplift area in the middle developed (Chen 2010). There are complex fault structures, strong magmatic activity and frequent seismic activity in this area. From 1530 to 2018, three earthquakes with $M \geq 6.0$ occurred along the Anninghe-Zemuhe fault zone in the region (Figure 1). The largest earthquake was the Xichang M 7.5 earthquake, which occurred
in 1850 (Xie et al. 2017). The analysis of tectonic stress characteristics showed that this area is in the process of large-scale horizontal shear and compression uplift deformation, and there is a relatively high background of strain energy accumulation (Wang et al. 2008; Zhang et al. 2007). These results indicate a high-risk level of strong earthquakes in Xichang area in the future (Hu et al. 2020; Lu et al. 2012). Therefore, it is urgent to expedite research studies on the risk of local casualties or people trapped in an earthquake.

3.2. Earthquake scenario

Generally, earthquake scenarios can be conducted by the deterministic method or the probabilistic method (Kijko et al. 2015; Lantada et al. 2010). For earthquake high-risk areas, the deterministic method can not only provide a useful reference for the improvement of regional targeted earthquake disaster preparedness and disaster-coping capability, but also distinguish the difference of disaster losses between daytime and nighttime, by comparing the earthquake disaster losses under the influence of the same earthquake intensity.

The Xichang area is one of the rare high seismic intensity zones in China. In the seismic intensity zoning of China, the fortification intensity of Xichang city is no less than degree IX (Chinese seismic intensity scale, corresponding to PGA 3.54~7.07 m/s², SAC (Standardization Administration of China) 2008). It is an earthquake high-risk region in China. Therefore, to better distinguish the risk differences of trapped people among different buildings during the daytime and the nighttime, this study adopts a given deterministic earthquake scenario (more targeted) to evaluate the risk of people trapped in earthquakes.

Currently available building damage probability matrices (DPMs) are still based on the seismic intensity in China, e.g. the baseline DPMs for different regions developed by Yin (1995). Thus, we used the shaking intensity as an earthquake hazard parameter based on the 2008 Chinese seismic intensity scale (SAC (Standardization Administration of China) 2008), and we chose intensity-based DPMs to assess the extent of structural damage to single buildings in this study. Previous investigations have found that there were hardly any collapsed buildings with a seismic intensity less than VIII in China. Thus, this study designs the seismic intensity IX degree as the given earthquake scenario; that is, the following analysis only focuses on the risk of people trapped in the collapsed buildings caused by a shaking intensity IX degree (corresponding to PGA 3.54~7.07 m/s²) in this study. The Chinese seismic intensity scale 2008 is the revised fourth edition of the shaking intensity table in mainland China. Over ten years after its implementation, it shows the scientific, reasonable, practical and efficient evaluation results in the actual application in mainland China. It is more suitable for earthquake disaster loss assessment using the Chinese seismic intensity scale in mainland China (Chen et al. 2004).

3.3. Structure building collapse rate

Locally oriented seismic vulnerability curves or building damage probability matrices are required for the assessment of earthquake casualties due to regional differences
worldwide (Chen et al. 2004; Karimzadeh et al. 2014). Generally, building damage grades can be divided into five categories in China: good (including no damage), light damage, moderate damage, heavy damage, and severe damage (Yin 1996). It is difficult to accurately determine the collapse rates among different building damage grades, due to the limitation of historical earthquake data. Preliminary investigations have found that the trapping of people during earthquakes is mainly caused by severely damaged buildings (Ma and Xie 2000b; Yin 1996). Severely damaged building means that most load-bearing components are seriously damaged, and the building structure is on the verge of collapse or has been destroyed, and there is no possibility of repair (SAC (Standardization Administration of China) 2008). Therefore, we considered the severe damage rate of different structural buildings at a particular intensity as its collapse rate in this study.

Affected by the same seismic intensity, the damage rate of buildings with different structures is different. To accurately reflect the characteristics of damaged buildings in Xichang city, this study used the Sichuan building DPMs from a previous study (He et al. 2002) to determine the collapse rate of each structural type resulting from an earthquake. Through the sampling survey of all kinds of buildings in Sichuan Province, the resistance index and damage matrix of individual buildings were obtained. Then, the building DPMs for four different regions were given by a statistical analysis of the structural damage proportions at different seismic intensities (from the Chinese seismic intensity scale) in Sichuan, China (the details can be obtained from He et al. 2002). Because Xichang city is located in southwestern Sichuan, this study adopted building DPMs suitable for southwestern Sichuan (Table 1).

According to the source of the building inventory data, the building structural types were divided into four categories: reinforced concrete structure, multistory masonry structure, single-story residential structure and other structures. This study considered the severe damage rates of 4 structural types at a specific intensity from Sichuan building DPMs as their collapse rates.

### 3.4. Population exposure in the single buildings

As mentioned above, many factors could influence the population distribution in a building. The use function of buildings can fundamentally affect the indoor rate and the population distribution during the daytime and nighttime. In this study, by distinguishing the use functions of single buildings, the daily population density of

| Structure types | Chinese Seismic Intensity Scale | Reinforced concrete | Multi-story masonry | Single-story | Others |
|-----------------|--------------------------------|---------------------|--------------------|-------------|--------|
| VI              | 0.00                           | 8.91                | 0.00               | 1.00        |
| VII             | 0.12                           | 20.98               | 2.00               | 5.00        |
| VIII            | 1.51                           | 32.41               | 6.00               | 19.00       |
| IX              | 18.77                          | 46.01               | 22.00              | 33.00       |
| X               | 50.01                          | 66.44               | 49.00              | 75.00       |
different functional buildings is evaluated. Then, based on the existing actual investigation work, the indoor population rate of single buildings with different use functions is analyzed during the daytime and the nighttime in Xichang area. Combined with daily population density and indoor rate, the indoor population density in a single building can be calculated for the daytime and the nighttime, respectively. The use function of the buildings is divided into 5 types in this study, including residence, commerce, public, industry and others. Among them, commerce, public, industry and others all belong to nonresidential buildings.

4.4.1. Daily population density

Daily population density, that is, the daily population number that the buildings could accommodate. For example, the number of population living in residential buildings at nighttime can be considered as the daily population density they can accommodate. The daily population density does not take into account the changes of population number due to the population mobility over time and it is static. Residential buildings play a main role in carrying most of the population at nighttime. While the distribution of daytime population can be regarded as the result of different travel purposes of urban population in residential buildings at nighttime. Therefore, it is necessary to determine the daily accommodation population density of the buildings with residential function, which can be expressed as:

\[
D_{ri} = \frac{TP}{\sum B_{ri}}
\]

where \( D_{ri} \) is the average population density per residential building area (person/m\(^2\)) in the study area; \( TP \) is the total number of population living in the residential buildings in the study area; \( B_{ri} \) is the area (m\(^2\)) of the residential building \( i \) in the study area.

The buildings with different use functions have different population accommodation capacities, which determines the population density accommodated by various buildings. Due to the data limitation, it is hard to get the actual daily population density of non-residential buildings. Thus, we introduced the daily population density coefficient (DPDC) of buildings (\( \beta_u \)) to obtain the daily population density of buildings with the use function \( u \). The coefficient \( \beta_u \) is determined according to the average generation rate of morning peak population flow per unit area of various buildings (\( \omega_u \)). We defined the ratio of the average generation rate of people flow per 10 thousand m\(^2\) of buildings with other functions \( \omega_u \) (non-residential) in the morning peak to that of residential buildings \( \omega_r \), as the DPDC of buildings \( \beta_u \) with

| Building use | Daily population density coefficients | Daytime | Nighttime |
|--------------|---------------------------------------|---------|-----------|
| Residence    | 1.00                                  | 0.46    | 0.95      |
| Commerce     | 1.18                                  | 0.38    | 0         |
| Public       | 1.40                                  | 0.65    | 0         |
| Industry     | 1.38                                  | 0.52    | 0         |
| Other        | 0.58                                  | 0.30    | 0         |

Table 2. The daily population density coefficients and the indoor rates of buildings.
different use function \( u \). The average generation rate \( \omega_u \) of morning peak population flow per unit building area represents the contribution rate of the population in various buildings \( u \) to the morning peak of the urban, which can reflect the population accommodation of buildings with different functions (Li et al. 2013; Zhang et al. 2010). According to the average generation rates of morning peak population flow per 10 thousand \( m^2 \) of different functional buildings (BTDRC (Beijing Transportation Development Research Center) 2007; RGTG (Research Group of Trip Generation) 2009; Li et al. 2013), combined with field investigation, the DPDC of different functional buildings (\( \beta_u \)) in Xichang city can be calculated (Table 2). Thus, the daily population density of the buildings with use function \( u \) (non-residential) can be expressed as

\[
D_{ui} = \beta_u \times D_{ri}
\]  

(3)

4.4.1. Indoor occupancy rate

Determining the indoor rate of residents in different periods of a day is of great significance to assess the actual population distribution in buildings over time. Moreover, the population indoor rates of buildings with different functions are different in the same period of time. Based on the characteristics of daily routines in Southwest China, we defined 7:00 am–09:59 pm (Beijing time) as the daytime period and 10:00 pm – the next 6:59 am (Beijing time) as the nighttime period. At present, there are two primary methods employed to determine the indoor rate: the probability method (Cheng 1993; Xiao et al. 2009) and the field survey method (Chen 2016; Li et al. 2001; Tian 2012; Yan 2013). Due to the probability method is difficult to distinguish the use functions of buildings, we used the previous investigations and the existing work on indoor rates (Chen 2016; Tian 2012; Zheng and Zhao 2020), to determine the average indoor rates of the buildings with different use functions during the daytime and nighttime in Xichang City (Table 2). Among them, the average indoor rate of residential (Chen 2016), commercial (Chen 2016; Zheng and Zhao 2020), public (Chen 2016; Tian 2012), industrial (Tian 2012), and other buildings (Tian 2012; Zheng and Zhao 2020) is 0.46, 0.38, 0.65, 0.52 and 0.30 during the daytime, respectively. At nighttime, the average indoor rate is 0.95 for the residential buildings and 0 for the non-residential buildings (Chen 2016; Tian 2012).

3.5. Rate of self-aid and mutual aid

Due to the complexity of human response behaviors, the SAMA rate is chosen as the indicator to estimate the postearthquake human response in the model, which can be considered as a comprehensive result of the human response following an earthquake. Previous studies and investigations have shown that SAMA is an important measure to estimate the magnitude of casualties following a disaster (Li 2006; Qu et al. 2010; Wang et al. 2012; Wei et al. 2017b; Xiu 2004). According to statistical data, approximately 85% of victims successfully escaped during the Wenchuan earthquake by themselves or through mutual rescue measures (Qu et al. 2010). Due to Xichang area and Wenchuan area all belong to Sichuan Province, China, the overall response
behaviors of local residents during an earthquake are comparable. Consequently, we conservatively determined the SAMA rate of victims as 85% during an earthquake based on the experience of Wenchuan earthquake.

### 3.6. Data and procedures

To assess the risk of people trapped in the single buildings following an earthquake, the basic datasets required mainly include the single building inventory (divided by structure type and use function) data and the corresponding population distribution data of the main urban area in Xichang city. The detailed single building inventory data are provided by the Sichuan Seismological Bureau, including building structure type, building area, use function and other parameters. Among them, the structure type and area of buildings are mainly obtained by remote sensing image extraction and field investigation. The determination of building use function is mainly based on the judgment of urban land use type, combined with the verification of on-the-spot investigation in the study area. The total number of buildings used in this study includes 15,223 single buildings located in the main urban area of Xichang city.

The population exposure data corresponding to the distribution of buildings is also one of the basic data needed in this study. Unfortunately, population distribution data in a single building are often unavailable for confidentiality reasons. For nighttime, nearly all residents are located in residential buildings, and the average daily population density per building area can be calculated based on the division of the total population and the total residential area. However, during the daytime, both residential and nonresidential buildings have residents in the room. In order to
obtain the average indoor rates of the different functional buildings during the daytime, we introduced the DPDC of buildings (Please refer to the above 3.4 part for details). The total population data of the main urban area in Xichang city comes from Xichang Statistical Yearbook 2019 (the latest available version), which provided the population data for 2018 (XSB (Xichang Statistics Bureau) 2019). The indoor rates of the different functional buildings during the daytime and the nighttime can be obtained based on the previous investigation work (Tian 2012; Chen 2016; Zheng and Zhao 2020; The details can be found in the 3.4 part).

4. Results

4.1. Structural types and functional distribution of buildings

Different structural types of buildings demonstrate different anti-seismic performances. Generally, reinforced concrete structural buildings have improved anti-seismic performance relative to multistory masonry structures, single-story buildings and other structures. Figure 2 shows the distribution of building structural types in the main urban area of Xichang city. The total number of buildings in the study area is 15,223, excluding the data without information or unable to collect. The reinforced concrete structure is the main structure type in the study area, which accounted for approximately 93.46% (14,228) of the total number; the single-story structure and the other structures accounted for 3.60% (548) and 2.17% (330) of the total, respectively (Table 3). The proportion of multimasonry structures is the lowest, accounting for only approximately 0.77% (117) of the total buildings.

At different times, the daily population flow in the city is also deeply affected by the use function of buildings. For example, during the nighttime, the population will be mainly concentrated in residential buildings, while nonresidential buildings (such as commercial or public buildings) will be closed, and there is basically no population distribution. In contrast, during daytime working hours, there will be a normal population flow distribution in nonresidential buildings. The time difference of this distribution will directly affect the actual population distribution in different functional buildings, which would further affect the accuracy of the risk assessment of people trapped in the collapsed buildings. Therefore, it is of great significance to distinguish the use functions of different buildings to accurately evaluate the distribution of casualties or people trapped in collapsed buildings. Figure 3 shows the distribution of buildings based on the use function of the buildings in the study area. Over 80% (12,186) of the total buildings are residential buildings in the study area. Commercial and public buildings accounted for 12.74% (1940) and 4.41% (671) of the total, respectively (Table 3). Industrial buildings accounted for approximately 1.82% (277)

| Building structures | Reinforced concrete | Multistory masonry | Single-story | Other |
|--------------------|---------------------|--------------------|--------------|-------|
| Percentage/%       | 93.46               | 0.77               | 3.60         | 2.17  |

| Building use       | Residence | Commerce | Public | Industry | Other |
|--------------------|-----------|----------|--------|----------|-------|
| Percentage/%       | 80.06     | 12.74    | 4.41   | 1.82     | 0.97  |

Table 3. Distribution of the buildings in Xichang City.
of the total. Additionally, approximately 148 buildings are for other uses, accounting for approximately 0.97% of the total.

4.2. Distribution of collapsed buildings

Figure 4 illustrates the collapsed building distribution in the study area under the background of earthquake intensity IX degree. The total area of collapsed buildings reached 4,368,599.85 m². Specifically, the collapsed reinforced concrete structure reached 4,258,682.36 m², accounting for approximately 97.48% of the total collapsed building area. The collapsed area of the single-story structure was approximately 71,036.68 m², accounting for approximately 1.63% of the total collapsed building area. The collapsed multimasonry structure and the other structures accounted for approximately 0.52% (22,522.61 m²) and 0.37% (16,358.20 m²) of the total collapsed area, respectively.

From the perspective of building use function, approximately 78.16% (3,414,441.61 m²) of the total collapsed buildings are residential buildings in the study area. Commercial and public buildings accounted for 14.09% (615,360.25 m²) and 6.42% (280,594.00 m²) of the total, respectively. Industrial buildings accounted for approximately 0.89% (38,924.54 m²) of the total. Additionally, approximately 19,279.46 m² of collapsed buildings are for other uses, accounting for approximately 0.44% of the total.

4.3. Distribution of indoor occupancy people

According to statistics, the total population of the main urban area of Xichang city, including the Beicheng, Xicheng, Dongcheng, Chang’an, Xincun and Changning
According to the above analysis of the residential area in the main urban area, it can be calculated that the daily population density of the average residential building area in the main urban area is 0.009 people per m². Based on the DPDCs mentioned above, it can be calculated that the average daily population density of commercial, public, industrial, and other functional buildings is 0.011, 0.013, 0.012, and 0.005 people per m², respectively.

Figure 5 shows the distribution of indoor people during the daytime and nighttime in the study area. During the daytime, there were 52 buildings with more than 100 indoor occupational people. The dense population is distributed in 25 residential buildings, 10 commercial buildings and 17 public buildings. Among them, the most densely populated area with more than 300 indoor people is mainly distributed in one residential building, one commercial building and one public building. At night, there are 214 residential buildings with more than 100 indoor occupational people, which are densely populated areas. Among them, the most densely populated area with more than 300 indoor people is mainly distributed in four residential buildings.

4.4. Risk distribution of people trapped in the collapsed building

Figure 6 demonstrates the risk of people trapped by collapsed buildings during the daytime and nighttime in the study area. The assessment results indicated that if the study area was stricken by an earthquake with seismic intensity IX in the daytime, approximately 1676 people would be trapped in the collapsed buildings, accounting for approximately 1.03% of the total regional population. Among them, there are...
eight buildings (1 residential building, 3 commercial buildings and 4 public buildings), the potential for trapped people of which would be over 5 individuals. In particular, the highest risk of the people trapped in the collapsed buildings was located in three buildings (one residential, one commercial and one public); the potential for trapped people would reach up to 9–11 individuals.

Figure 5. Distribution of the indoor occupation people in the studied area.
If an earthquake occurs at night, the risk of population trapped in the collapsed buildings would increase significantly. Our results showed that there would be approximately 3286 people trapped in collapsed buildings if an earthquake with seismic intensity IX occurs at night in the study area, which accounts for approximately...
2.02% of the total regional population. There would be 26 residential buildings, and the potential for trapped people would be over 5 people. The highest risk of the people trapped in the collapsed buildings was also located in two buildings, and the potential for trapped people would be over 10 people. Among them, the largest number of trapped people would reach up to 23 people in one residential building.

5. Discussion

5.1. Risk distribution of trapped people in Xichang city

The risk of people trapped in collapsed buildings caused by an earthquake in the Xichang area is high. Our results showed that regardless of whether it is daytime or nighttime, the number of people trapped in the collapsed buildings caused by seismic intensity IX accounts for approximately 1–2% of the total regional population. This result is consistent with a previous study on the 2014 Ludian earthquake, in which the proportion of trapped people in the IX intensity area accounted for approximately 1.08% of the total regional population (Wei et al. 2017b). This result not only shows the high risk of trapped people in an earthquake in the Xichang area, but also verifies the rationality of our assessment results. The low seismic performance of buildings is the most important factor causing a high risk of people trapped in the collapsed buildings in the Xichang area. Although the Xichang area is one of the few areas with IX-degree fortification in China, it is found that the vulnerability of buildings is relatively high, especially under the influence of intensity IX or above, according to the historical statistics of regional building damage caused by earthquake disasters (He et al. 2002). For example, the vulnerability proportion of reinforced concrete structure buildings under seismic intensity IX reaches 18.77%, which is not only much higher than those of other areas (such as 0.56% in Ganzi-Aba area, 5.40% in East Sichuan) in Sichuan Province but is also higher than that in the Yunnan area (nearly good under intensity IX), which is on the border with southwest Sichuan, China (He et al. 2002; Zhou et al. 2007). The vulnerability of other structural buildings is also relatively higher than those in other areas of Sichuan Province, China (He et al. 2002).

Additionally, due to the difference in the population density and distribution, the risk of trapped people in the daytime and at nighttime caused by the same earthquake level is significantly different. Our results showed that under the impact of the earthquake with intensity IX, the number of potential trapped people in the Xichang area at night was nearly two times (196%) that during the daytime. Similarly, the concentration point distribution of people trapped in an earthquake at night is much wider than that during the day. During the daytime, due to the low rate of people in a room or a building, the population distribution is more dispersed, and the concentration point of the population trapped (more than 5 people) will be expanded to 26, and the number of trapped people in the highest potential risk point is as high as 23. The difference in the use functions of single buildings is the main factor affecting the difference in the population density and distribution between the daytime and
nighttime. At night, the vast majority of the population is basically distributed in residential buildings. However, during the working hours of the daytime, the population is distributed from residential buildings to non-residential buildings, which results in the risk change of population exposure and people trapped over time.

Our results further confirmed that due to the difference in population distribution, there are significant differences in the temporal and spatial distributions of people trapped in an earthquake during the daytime and at nighttime. This is consistent with the conclusions of previous studies on casualty assessment (Cheng 1993; Coburn and Spence 2002; Freire 2010; Yuan et al. 2019). For example, the work of Freire and Aubrecht (2012) in the Lisbon Metropolitan Area showed that from night to day, the population exposed to the two highest seismic levels increases, while the number of persons exposed to the two lower levels decreases. Recently, Yuan et al. (2019) found that the differences between the daytime and nighttime casualty distributions were mainly due to differences in the daytime and nighttime population distributions in Haidian District, Beijing, China. In summary, knowing the spatiotemporal distribution of the population at the local scale is fundamental for disaster risk analysis and emergency management. High spatial resolution population distribution is of great practical significance for accurately assessing the risk of people trapped.

5.2. Implications for local risk reduction

Time is of significant essence in a post-earthquake area, and thus any delays toward understanding the scale of a disaster would prove to be both socially and economically costly. Unfortunately, the available actual information of disaster is very limited during the early stages of a destructive earthquake. This limitation can subsequently cause excessively long emergency start-times and delays in the allocation of emergency supplies (Huang et al. 2015). The risk assessment of people trapped in an earthquake based on the level of single buildings can provide more clear directional guidance for postearthquake emergency rescue and material allocation, which could minimize the emergency rescue response time and improve the emergency rescue efficiency, to reduce casualties.

For local disaster-coping, improving the seismic performance of buildings is the basic way to reduce the risk of regional people trapped in an earthquake. The overall seismic performance of buildings in the Xichang area is lower than that in other areas of Sichuan Province, China (He et al. 2002). Therefore, it is important to vigorously improve the overall seismic performance of local buildings, strengthen or transform dangerous old buildings to reduce the seismic vulnerability of building structures, and reduce the risk of people trapped in a collapsed building caused by an earthquake. At the same time, it is necessary to expedite investigations and study the law of regional population flow. The difference in the indoor population density will directly affect the accuracy of the assessment results for causalities at different times after an earthquake (De Lotto et al. 2019; Freire and Aubrecht 2012; Jia et al. 2014), which could be the major guidelines for identifying the emergency supply demand and allocation of rescue resources. The risk assessment of people trapped at the scale of single buildings with use functions could more significantly distinguish the
characteristics of population flow, and more accurately evaluate the risk difference of causalities during the daytime and nighttime. Therefore, it is of great practical significance to strengthen the investigation of single buildings and the indoor occupation rate in the area, to develop fine-scale population spatial-temporal distribution data and improve the accuracy of regional assessment of casualties. At the same time, with the rapid development of mobile information and big data technology, location-based mobile service data and Point of Interest (POI) data can also be widely used in the research on the dynamic spatial and temporal changes in human activity behaviors, to strengthen the understanding of the law of dynamic population flow and distribution (García-Palomares et al. 2018; Li et al. 2019; Shaw et al. 2016; Wu et al. 2018; Xia et al. 2020).

In addition, enhancing the awareness of earthquake disaster prevention and preparedness capability is also an effective way to reduce the risk of local earthquake disasters. Many studies have shown that the public’s cognition and effective response to disasters are also effective ways to reduce disaster risk (Shi et al. 2005; Su et al. 2008; UN/ISDR 2005; Wei et al. 2013). A previous study found that although the disaster cognition and response capability in the Sichuan area has improved since the 2008 Wenchuan earthquake, its overall level is only at a moderate level (Wei et al. 2020, 2021). Due to the difficulty of predicting an earthquake and the great destruction of earthquake disasters, the risk awareness of earthquake disasters needs to be continuously improved, including the propaganda and education of earthquake disaster knowledge and the training and practice of earthquake disaster prevention and reduction skills.

5.3. Uncertainty and limitations

There is no doubt that there are some limitations in this study. In addition to some common limitations in similar studies, the main deficiency of this study is the lack of an accurate measurement of the population density in single buildings due to confidentiality reasons. In this study, we introduced the DPDC of buildings to identify the differences of the daily accommodation population density for different functional buildings. At the same time, based on the characteristics of local human routines and the existing actual investigation results, the average indoor rate of different functional buildings during the daytime and nighttime is provided. Our assessment results reflected that this method will not affect the rationality of the risk assessment results on the regional population trapped in collapsed buildings. However, by further refining the use function classification of local single buildings, it is possible to more accurately identify the differences of their daily accommodation population density, to further improve the assessment accuracy of population exposure in future. Another limitation is the evaluation of the indoor occupancy rate during the daytime and at nighttime. Although we have identified the differences of indoor rates among different functional buildings, which has been less considered in previous studies, the impact of time change only reflects the differences between the daytime and at night. In fact, due to human activities, the indoor occupancy rate in the buildings changes as time over, especially during the daytime of working days. Therefore, it is also
important to further refine time resolution of population indoor rate (such as hourly changes) in different functional buildings to obtain finer spatio-temporal distribution of population. According to our empirical study results on the 2014 Ludian earthquake, the error of the trapped people in the earthquake evaluated by the similar method is between $-16.5\%$ to $+3.2\%$ (Wei et al. 2017b). In the future, with the completion of basic data, the assessment accuracy of people trapped or casualties with high spatio-temporal resolution could be further improved during an earthquake, by strengthening the study of population flow law based on dynamic mobile big data. Nevertheless, this study proposed a rapid risk assessment method for people trapped in an earthquake based on the single buildings, by distinguishing their use functions and identifying their differences of indoor population density. This method can also be applied in other regions as long as the parameters and basic data required by the model are obtained. Ultimately, the applicability of the method requires further examination using the actual earthquake case studies.

6. Conclusions

This study constructed a risk assessment model of people trapped in an earthquake based on the distribution of single buildings and population data. The application of the assessment model in Xichang city showed that the results from the model are reasonable. Xichang is an area with a high risk of people trapped in an earthquake. The number of people trapped in collapsed buildings caused by seismic intensity IX accounts for approximately 1–2% of the total regional population. Due to the difference in the population density and mobility, the risk of trapped people in the daytime and at night caused by the same earthquake is significantly different. Under the impact of an earthquake with intensity IX, the number of potential trapped people in the Xichang area at night is nearly two times (196%) greater than that during the day.

The low seismic performance of buildings is the most important factor causing the high risk of people trapped in the collapsed buildings in the Xichang area. The use functions of buildings are also an important factor affecting the risk distribution of regional people trapped, which could significantly affect the indoor rate and population mobility during the daytime and nighttime. Improving the seismic performance of buildings is the basic way to reduce the risk of regional people trapped. It is also necessary to increase the investigations and studies of the law of regional population flow, by introducing mobile big data and high-precision household census data. Additionally, enhancing the awareness of earthquake disaster prevention and preparedness capability is also an effective way to reduce the risk of local earthquake disasters.

The accuracy of the evaluation results depends on the acquisition and completeness of the basic data. Building-level data could provide more practical disaster information for ESAR and decision-making, due to it can significantly distinguish the use functions of single buildings and population distribution during the daytime and nighttime. Although there are some limitations in this study, it could not have a fundamental impact on the accuracy of the risk assessment. This study is a useful
attempt based on the data of a single building with different use functions in the Xichang area. It offers a simple and rapid calculator for trapped people losses based on direct empirical data. The information from our assessment on people trapped in single buildings could provide valuable guidance in determining the rational allocation of rescue forces and resources. By replacing the corresponding data, this model can also be applied to the risk assessment of people trapped in other areas of China. Of course, the adaptability and rationality of the evaluation results from the model need to be further evaluated in other areas of China. With the abundance and completeness of basic data, the accuracy and application of the assessment results can be further improved, which could be more helpful in the determination of the key rescue areas, to improve the rescue efficiency and reduce casualties.

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**Data availability statement**

The data that support the findings of this study are available from the corresponding author, Wei BY.

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