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ASSESSING BUILDING VULNERABILITY TO LANDSLIDES IN THE THREE GORGES RESERVOIR AREA OF CHINA

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Landslides are among the most destructive natural hazards, causing significant loss of life and damage to buildings. The Three Gorges Reservoir Area (TGRA) of China is particularly vulnerable to such events. Building vulnerability assessments are crucial for disaster risk management, linking building damage to landslide intensity and structural characteristics. However, many existing studies are site-specific, limiting their applicability to other regions. This study assesses the building vulnerabilityto landslides in the TGRA using two case studies. SBAS-InSAR-derived differential settlement is combined with in-situ building damage surveys to evaluate building vulnerability. Fragility curves for brick-concrete buildings with shallow foundations, developed from Landslide I, are applied to predict building damage levels in Landslide II. The predictions are compared with survey data to assess the transferability of the fragility curves. The results confirm their reliability and transferability and provide valuable insights for landslide prevention and mitigation in the TGRA.

Keywords: Building vulnerability; fragility curve, landslide, SBAS-InSAR, damagelevel.

1. Introduction

Landslides are major geological hazards in the Three Gorges Reservoir Area(TGRA) of China, posing significant threats to the environment, infrastructures, and human activities (Wei et al., 2023). Since the first impoundment of the reservoir in 2003, numerous landslides have been formed in the TGRA and causedcontinuous damage (e.g., widespread cracking and structural tilting)to infrastructures such as buildings, bridges, and highways(Chen et al., 2022). To better manage landslide risk, a crucial step is to assess different buildings' vulnerability under different intensities of landslides.

Existing assessment models for building vulnerability to landslides include qualitative approaches based on experience or indicators(Bera et al., 2020) and quantitative approaches based on investigation data (Peduto et al., 2017) or mechanics (Chen et al., 2020). These models relate landslide intensity to building damage, often represented by fragility curves, matrices, or functions (Luo et al., 2023).Among them, fragility curves estimate the probability of exceeding different damage states for a given hazard, and they are widely used in practice as they are able to explicitly account for hazard characteristics, building failure mechanisms, and associated uncertainties. However, the development of fragility curves heavily relies on building damage datasets obtained through in-situ surveys, which not only increases fieldwork demands but also results in fragility curves that are often highly site-specific and have limited transferability.

To address this limitation, this study uses two landslides in the TGRA as case studies. The fragility curves for brick-concrete buildings with shallow foundations are developed by differential settlement from remote sensing and in-situ survey of building damage from Landslide I. To evaluate the reliability and transferability of the fragility curves, they were applied to predict the damage levels of buildings in Landslide II and validated against in-situ survey data. Once validated, the fragility curves can serve as a reliable tool for predicting landslide-induced building damage levels without in-situ surveys in the TGRA.

2. Study area and multi-source survey information

Landslide I (110°00'51"E, 31°7'55"N) is located in the center of the TGRA, as shown in Fig. 1(a). The landslide covers an area of 30×10^4 m², with dimensions of 600 m in length and 500 m in width, and elevations ranging from 880 m to 1200 m. It has an estimated volume of 900×10^4 m³, a mean sliding surface depth of about 30 m, and a primary sliding direction of 340°.First deformed in July 2016, the landslide is currently in a creeping deformation stage, primarily at its trailing edge. Elements at risk include 126 buildings housing 524 residents, and 1.70 km long National Highway.

With the help of the Chongqing Bureau of Geology and Minerals Exploration, a comprehensive field investigation was carried out in November 2023to assess the characteristics, distribution, and severity of building damage over the past seven years. The survey covered 118 affected buildings, gathering detailed data on building geometry, structure (e.g., number of floors, materials, construction year, foundation type), damage records (e.g., crack size, number, and direction), and demographic information (e.g., permanent residents, gender and age distribution) (Figs. 1(b-g)).The surveyed buildings, categorized by their building types (64.4% shallow, 21.2% piled, and 14.4% adobe) are highlighted in Fig. 1(a).

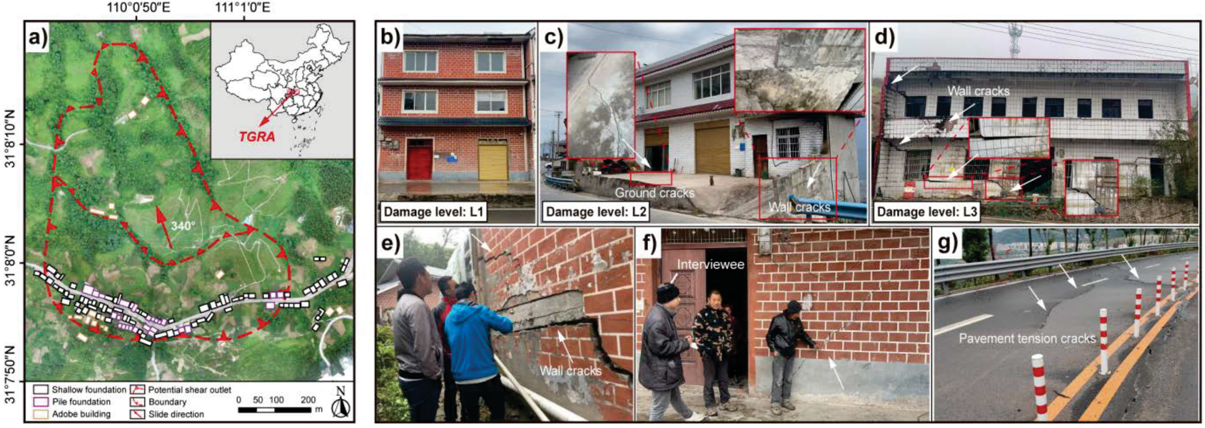

Fig.1 Landslide I and in-site survey: (a) location;(b-d) typical buildings with different damage levels; (e,f) crack patterns of brick-concrete buildings; and (g) pavement tension cracks.

In addition, remote sensing techniques such as the interferometricsynthetic aperture radar (InSAR) are widely used in literature to measure ground deformation on a regional scale (Cook et al., 2023). In this study, the small baseline subset (SBAS) -InSAR time-series technique is used to analyze the settlement of each building in the studied area based on C-band SAR imagery from Sentinel-1A satellites, acquired in interferometric wide swath mode with VV polarization. A total of 221 ascending orbit images, captured between June 2016 and December 2023 at an incidence angle of 41.4°, were selected for processing. Ground deformation data in the line-of-sight direction were retrieved using SBAS-InSAR analysis, with a 30m-resolution SRTM-DEM from NASA as the reference DEM and ESA’s precision orbital data for orbital corrections.

3. Building vulnerability assessment

To assess the building vulnerability subject to Landslide I, buildings within the landslide area are first classified into different types: most of the buildings are brick-concrete structures, with a small proportion of adobe buildings. Only those brick-concrete structures with shallow foundations are taken into consideration in this study. The damage level in masonry and brick structures is widely classified into six levels, ranging from negligible (D0) to very severe (D5). D0 to D2 are typically associated with aesthetic damage, such as fine cracks, which can be easily addressed during routine decoration or with minor repairs. Beginning at D3 and D4, the building may experience moderate loss of functionality, requiring maintenance. At D5, there is a significant risk to structural safety or stability. Following Peduto et al. (2017), this study combines D0 to D2 into L1, merges D3 and D4 into L2, and classifies D5 as the most severe level L3, resulting in a simplified three-level damage grading criterion, as shown in Table 1.According to thedamage grading criterion,the buildings are catalogized into distinct damage levels for statistical analysis.

Table1. Simplified damage grading criterion and correspondingcrack width to walls along with their description.

Degree of damage	Damage description	Crack width (mm)
L1(slight)	Aesthetic damage is characterized by hairline/fine cracks that can be easily treated during normal decoration or require easy repair work.	< 5
L2(moderate)	Cracks are prominent, requiring opening and patching by a mason. Doors and windows may jam, and service pipes may fracture.	5 to 25 or number e3
L3(severe)	Widespread cracking with structural damage requiring major repairs, including partial or complete rebuilding. Settlements may cause wall tilt and instability, necessitating building evacuation.	>25

Note that buildings with fewer floors and smaller spans are more vulnerable to differential settlement(Miano et al., 2022). Since most buildings in Landslide I are 1- to 3-story brick-concrete structures with relatively small spans, it is reasonable to assess building fragility in this region using differential settlement as an indicator of landslide intensity on structural integrity. The differential settlementcan be defined as the maximum vertical displacement difference (”$_k$) between any two points within the k-th building's foundation, where the vertical ground deformation is extracted using the SBAS-InSAR technique.

The probability distribution of differential settlement values within the same damage level can be established. Since differential settlement” is non-negative and skewed, ln(”) is assumed to follow a normal distribution with parameters $\overline{\Delta}_i$ (median) and $^{2}{}_{i}$ (log-standard deviation). Given a certain ” value, the probability of exceeding a specific damage level L_i can be approximately expressed in the form of lognormal distribution as:

$$P(Damage \geq L_i \mid \Delta) = \Phi[\frac{1}{\beta_i}\ln(\frac{\Delta}{\overline{\Delta}_i})] \quad (i = 1, 2, 3) \qquad (1)$$

where ¦ [.] is thecumulative distribution function of standard normal distribution. By developing exceedance probability models for each damage level, a family of building fragility curves is established.The probability of being a specific damage level L_i can be obtained by subtracting$P(Damage e L_{i+1}|”)$ from $P(Damage e L_i|”)$. Using the fragility curves, it is easy to determine the damage state of a building based on its differential settlement.

4. Results and discussion

4.1.*Building damage surveyand InSAR results*

The building damage levels for pile and shallow foundation buildings within Landslide I are determined according to Table 1. Notably, 39.4% of brick-concrete buildings with shallow foundations are classified as L1, while 38.2% are L2 and 22.4% are L3. In contrast, 80% of pile foundation buildings are classified as L1, with the remaining 20% as L2 or L3. These results suggest that pile foundations help mitigate the impact of slow-moving landslides on buildings. In addition, the vertical average deformation rate with a spatial resolution of 10 meters is obtained using the SBAS-InSARtechnique for the period from June 2016 to December 2023, as shown in Fig. 2.The deformation rates ranging from -64.56 to 34.99 mm/year, with positive and negative values indicating surface uplift and subsidence, respectively.

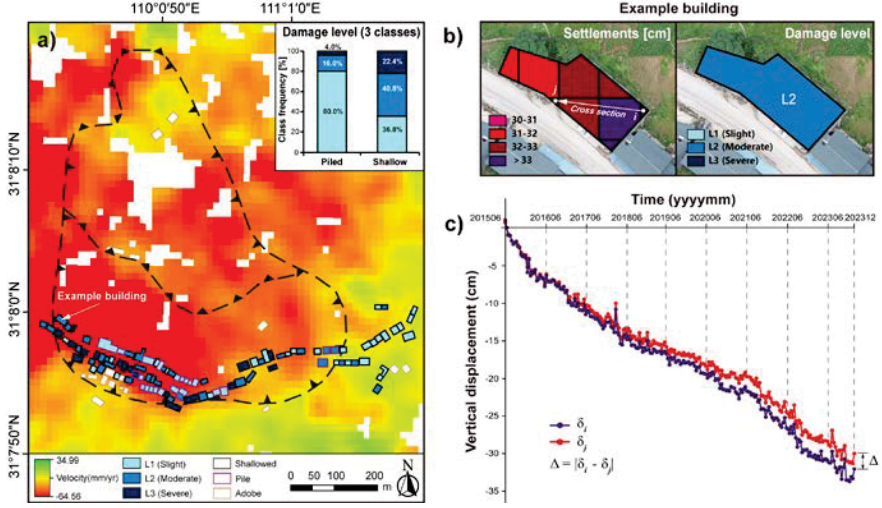

Fig. 2 Building survey and InSAR results: (a) building damage levels and vertical deformation rates within Landslide I; (b) example of a building; (c) evolution of vertical displacements from June 2015 to December 2023.

4.2.*Fragility curves*

Given the prevalence of brick-concrete buildings with shallow foundations in Landslide I, deriving fragility curves for this building type is crucial for landslide prevention and mitigation. The survey data of damage level and differential settlement for different buildings are presented in Fig. 3(a). As building damage increases, the median ($\overline{\Delta}_i$) of differential settlement rises and the standard deviation ($^{2}{}_{i}$) decreases, consistent with experience.

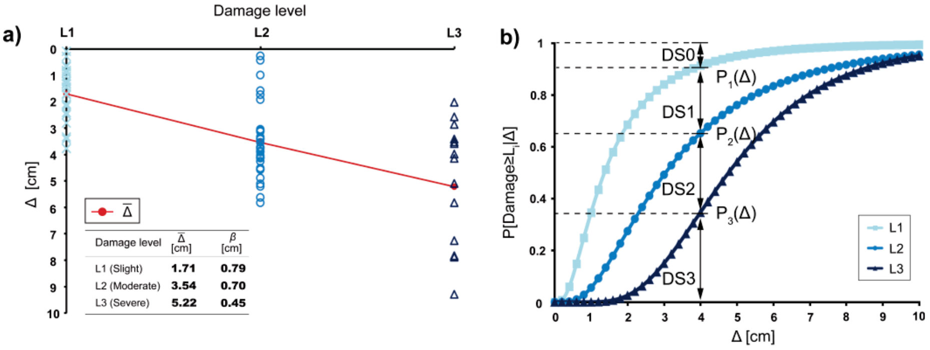

Fig.3Vulnerabilityof brick-concrete buildings: (a) damage level vs. differential settlementsurvey data; (b) fragility curves.

The fragility curves, using exceedance probabilities (P_1(”), P_2(”), and P_3(”)) and the defined damage states (DS1, DS2, DS3), allow for calculating the damage probability distribution of a building based on its differential settlement (”). Specifically, for a given ” , the probability of the building being in DS1 is P_1(”)-P_2(”), in DS2 is P_2(”)-P_3(”), and in DS3 is P_3(”). The damage state with the highest probability is considered the predicted damage level of the building.

4.3. *Validation*

To assess the reliability and transferability of the established fragility curves, they are applied to predict the damage levels of buildings in Landslide II with similar geological characteristics and validated using in-situ survey data. As shown in Fig. 4, Landslide II includes 36 brick-concrete buildings with shallow foundations, excluding two adobe buildings. The predicted damage levels match the ground truth for 26 buildings, resulting in a high accuracy of 72.2%. The damage levels areslightly underestimated for the remaining ten buildings.

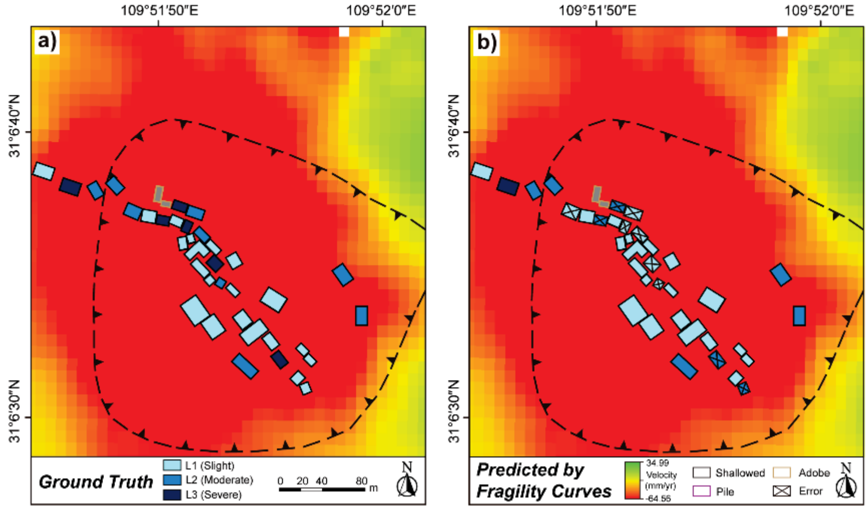

Fig.4The damage levels of buildings in Landslide II: (a) Ground truth; (b) Prediction.

5. Conclusion

This study assesses the building vulnerability of brick-concrete structures with shallow foundations. Differential settlement derived from SBAS-InSARtechnique represents the impact of landslide intensity on buildings, and combined with in-situ building damage surveys, fragility curves are developed. Using two landslides in the TGRA of China as case studies, the study addresses the limitations of existing fragility curves, which are highly site-specific and lack transferability. The fragility curves derived from Landslide I are used to predict building damage levels within the range of Landslide II.

The results demonstrate that fragility curves provide a fast and reliable tool for preliminarily predicting landslide-induced building damage levels based on differential settlement, without requiring in-situ surveys. This validates the reliability and transferability of the fragility curves and provides valuable insights for landslide prevention and mitigation in the TGRA.

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