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Exploring disaster resilience strategies for temple spaces: evidence from Longmen Mountain area in Sichuan

Yue Dai¹, Baofeng Di^{2,3} ✉, Yajie Zeng², Qing Pei^{4,5}, Junhui Li², Gang Chen⁶, Andreas Nienkötter^{2,7} & Yu Qiao⁸

Traditional temple spaces in the Longmen Mountain area of Sichuan Province, shaped by natural ecosystems and Chinese geomancy, reflect adaptability in the human–land relationship. However, their long-term survival in hazardous environments remains unclear. This study investigates their disaster-prevention adaptability using field surveys, geospatial data, and quantitative methods such as GIS spatial analysis. Results show that temples in disaster-prone areas favor flat terrains like towns, suburbs, and mountain platforms. As altitude and slope increase, the proportion of disaster-prevention space also rises, demonstrating adaptive principles. Complex spatial forms diversify disaster-prevention spaces, while simpler forms enable quicker refuge establishment. These findings provide insights into disaster prevention planning for modern human settlements.

In China, Buddhism is the oldest imported religion. Buddhist temples serve as enduring witnesses to the country's historical development and human civilization, forming an integral part of its cultural heritage¹. According to the United Nations Educational, Scientific, and Cultural Organization (UNESCO), cultural heritage sites are vulnerable to natural hazards². Consequently, traditional Chinese temples exhibit a strong connection with natural disasters.

The existing research indicates that temples have the potential to contribute to disaster preparedness, response, and recovery in various ways. Firstly, it is crucial to recognize that people's perceptions of disasters are deeply intertwined with their cultural and religious beliefs³. As tangible embodiments of Buddhist culture, temples offer spiritual solace and help alleviate the psychological trauma caused by disasters⁴. For example, during the 2004 Indian Ocean tsunami, numerous Buddhists provided immediate psychological support to the victims⁵. Similarly, during the 2008 Wenchuan earthquake, many monks opened their temples, preached the Dharma, and provided solace to the affected population. In the aftermath of the 2010 Yushu earthquake, thousands of monks from temples across Yushu actively participated in relief efforts⁶. In disaster situations, guided by the humanistic principles of faith⁷, temple personnel and facilities often demonstrate flexible rescue measures and provide psychological support. It is noteworthy that Buddhists encourage faith in miracles while simultaneously employing protective measures such as evacuation^{8,9}.

Secondarily, TT complexes have demonstrated significant potential in disaster risk mitigation through their architectural configurations, environmental contexts, and spatial layouts^{10–12}. Numerous studies have demonstrated that temples possess disaster prevention capabilities. TTs mitigate earthquake impacts through structural innovations and material adaptability. Central pillars and layered designs ensure stability^{13,14}, while lightweight wooden materials, combined with flexible mortise-and-tenon joinery—a hallmark of traditional Chinese construction—offer long-term resilience, even without modern engineering techniques¹⁵. At the spatial level, the spatial layout of temples is generally harmonized with the local environment to enhance resilience. For instance, temple complexes in the Himalayan Valley are strategically located to avoid avalanche hazards¹⁶. Similarly, in China, TT, due to their initial construction adhering to principles such as adapting to the terrain and following the waterways, can be located in a relatively safe position on the mountain, enhancing their long-term disaster prevention resilience^{17,18}. As cultural heritage, temples have a significant positive impact on the stage of disaster system construction and disaster prevention preparedness. For instance, the besakin community conveys disaster prevention knowledge through religious ceremonies organized by temples¹⁹, and Buddhist organizations promote "compassion" to encourage mutual assistance in disaster prevention within the community²⁰. The regular social services provided by temples (such as medical care and elderly care) have laid the foundation for disaster

¹College of Architecture and Environment, Sichuan University, Chengdu, 610040 Sichuan, China. ²Institute for Disaster Management and Reconstruction, Sichuan University-Hong Kong, Polytechnic University, Chengdu, 610200 Sichuan, China. ³Center for Archaeological Science, Sichuan University, Chengdu, 610040 Sichuan, China. ⁴Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong, 999077, Hong Kong. ⁵Department of Chinese History and Culture, The Hong Kong Polytechnic University, Hong Kong, 999077, Hong Kong. ⁶Yaan Emergency Management Bureau, Sichuan, 625499 Sichuan, China. ⁷Faculty of Mathematics and Computer Science, University of Münster, Münster, Germany. ⁸Chengdu Piesat Information Technology Co, Chengdu, 610040 Sichuan, China. ✉e-mail: dibaofeng@scu.edu.cn

prevention. For instance, after the 2004 Indian tsunami, many temples, based on their daily free clinics, convalescent centers, and other social welfare functions, were quickly transformed into temporary shelters for disaster victims after the disaster, avoiding the waste of redundant construction of temporary disaster shelters in the local area²¹. Similarly, the local government has also actively collaborated with local temples, distributing supplies through the temples and leveraging their existing belief systems to enhance the efficiency of disaster relief²². Temple's stockpiles of food, water, and other essential supplies make it an accessible and reliable shelter during disasters. In many countries, including Japan and South Korea, temple communities promptly transformed their facilities into shelters and open spaces during natural disasters. On a physical level, the temple's stockpiles of food, water, and other essential supplies make it an accessible and reliable shelter during disasters. Tone et al.²³ utilized landscape model parameters to quantify the distribution and spatial changes of Japanese temples as refuge spaces since the Edo period. Kotani and Limsakri et al.²⁴ analyzed a single temple and discovered that its open spaces could serve as refuge areas. However, due to the relatively shorter history and limited temples in these countries compared to China, comprehensive patterns of temple space utilization for refuge and disaster prevention remain unexplored.

Numerous studies have identified “people-oriented and adapted to local conditions” as the core principle of refuge site selection^{25,26}. This principle closely aligns with the traditional temple site selection concept of “harmony between heaven and man, and adaptation to local conditions”^{27,28}. Modern disaster prevention planning for refuge site selection considers various factors, including geological conditions, topography, hydrological systems, ecological environments, and human factors, to minimize disaster risks. This approach parallels the “feng shui” theory of temple siting²⁹. The first step in temple site selection, guided by the principles of “dragon, sand, water, and point,” involves assessing the stability of the mountain, drainage and lightning protection, as well as the local microclimate³⁰. Historically, temple site selection demonstrated strong environmental adaptability, leading to the establishment of numerous settlements around temples³¹. The development and growth of these settlements provide evidence of the disaster prevention benefits inherent in temple site selection. Although numerous studies have explored the disaster avoidance characteristics of temple siting from the perspectives of Feng Shui culture and historical changes³², most focus on qualitative analyses^{33,34}. Quantitative investigations into the relationship between temples and disaster-prone environments remain limited.

Open spaces (OS), which facilitate the gathering, evacuation, and transfer of disaster victims, represent a key research focus in disaster prevention and resilience. Many researchers have attempted to quantify open spaces, with most studies focusing on the evaluation of green open spaces. The number, area, and shape of open spaces are often used as key indicators to assess regional disaster prevention capacity^{35–38}. However, the disaster prevention potential of temples as open spaces is often overlooked. The “square enclosure” spatial layout of temples unintentionally creates unique evacuation routes and shelters within temple sites^{39,40}. The “beaded” layout of temples includes passageways and bridges that connect open spaces, ensuring unobstructed escape routes^{41–44}.

The Longmenshan region lies along the Longmenshan fault zone, one of China's most seismically active crustal fault systems. Significant stress

accumulation along the faults indicates a persistent risk of large earthquakes, posing long-term threats to human settlements in this region^{45,46}. However, in this disaster-prone environment, TT have demonstrated remarkable adaptability, persisting over time as valuable cultural heritage and showcasing resilience to disaster conditions^{47–49}. For instance, on May 12, 2008, the Wenchuan earthquake devastated thousands of settlements, schools, and factories in the Longmenshan region⁵⁰. One of the most severely affected structures was the maternal and child health care hospital in Shifang City. The hospital building sustained severe damage, rendering it incapable of accommodating newborns and pregnant women. Emergency services relocated them to the nearby Luohan Temple. The Luohan Temple sustained minimal damage, offering ample refuge space and clear pathways, and served as a safe haven for pregnant women for nearly two months (Fig. 1). Such cases are not isolated. Post-disaster investigation reports indicated that traditional temples endured less damage compared to residential buildings⁵¹. They frequently served as critical shelters for nearby residents.

This research aims to summarize the disaster prevention experience of TT to guide spatial planning for human settlements in disaster-prone areas. Uncovering the wisdom of traditional Chinese construction for disaster prevention, as demonstrated by temples, could contribute to improving the global disaster prevention planning system and enhancing the understanding of traditional Chinese culture worldwide. The key innovations of our study include: (1) This paper initiates an investigation into the relationship between the geographical locations and spatial layouts of temples in the Longmen Mountain area and their surrounding disaster environments. Furthermore, we systematically classified and thoroughly analyzed the open spaces within traditional temples. (2) We defined disaster prevention spaces as a research index for evaluating the disaster prevention adaptability of temple layouts. This index includes the size, quantity, and types of disaster prevention spaces. It further aimed to summarize the principles underlying the disaster prevention adaptability of temples. Given the region's unique geological environment, this study focuses on earthquakes, debris flows, and other mountain-related natural disasters.

Methods

Study area

The Longmen Mountain Area in Sichuan Province is located northwest of the Sichuan Basin and is the main area of the Longmen Mountain overlying structure^{52,53}. At the environmental level, the risk of major earthquakes and mountain floods in the study area is extremely high. Therefore, how to achieve disaster prevention and mitigation for the residents in this area has always been one of the important research directions. On the cultural level, the Longmen Mountain Area is home to multiple ethnic groups such as Han, Tibetan, Qiang, and Yi. These different ethnic groups have coexisted for a long time and have engaged in cultural exchanges, making it a convergence point for multiple ethnic groups and religions. Therefore, many temple sites in the Longmen Mountain Area are widely distributed and have formed a religious site network within the Longmen District. It serves as a social hub foundation for disaster prevention and mitigation that can be utilized. Further research has found that the temples in the Longmen Mountain Area are widely distributed and closely related to the major earthquake sites and major fault zones (Fig. 2). They are far from merely cultural heritage landscapes but also places for residents to conduct large-scale social activities. These temples

Fig. 1 | A comparison of the situation at Luohan Temple and the Maternal and Child Health Hospital during the Wenchuan Earthquake.

a Wenchuan earthquake Shifang maternal and child health care hospital dangerous room. **b** Wenchuan earthquake Shifang arhat Temple emergency shelter. Source: <https://sc.sina.cn/news/m/2021-05-13/detail-ikmxzfmm2202258.d.html>.



Fig. 2 | The scope of the study area, the locations of historical earthquake sites of magnitude 6 or above in the Longmen Mountain Area of Sichuan Province, and traditional temples in the Longmen Mountain Area of Sichuan Province. Source: <https://www.sara.gov.cn/resource/common/zjcxccxt/zjhdcjsjbx.html>.

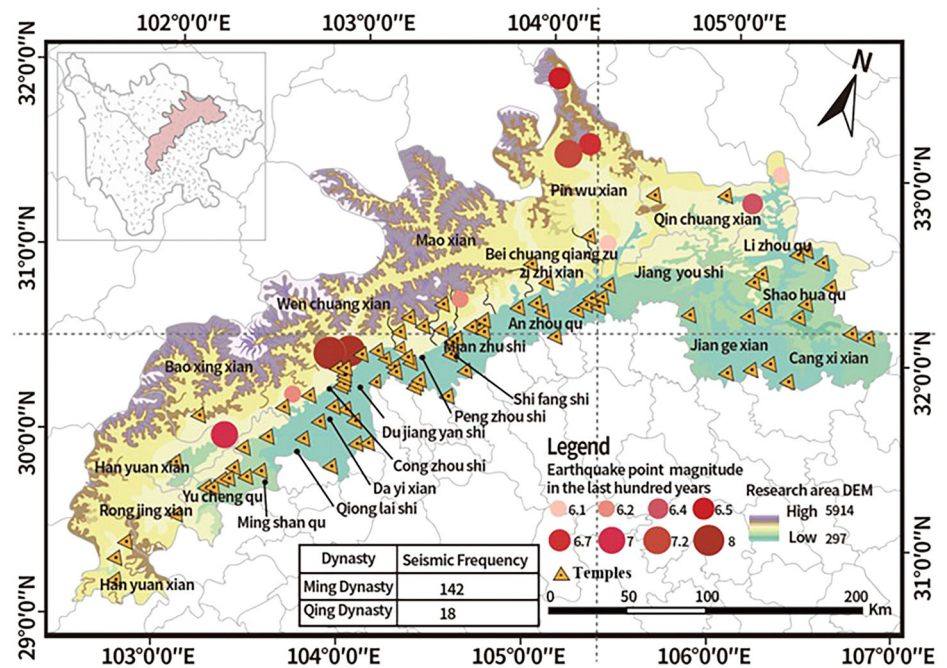


Table 1 | The criteria for identifying traditional temples

Standard dimensions	Specific contents and norms
Layout Principles	1. Axial symmetry with a three-courtyard system, religious activity areas (mountain gate, main hall) in the front, living areas in the rear 2. Buddhist temples have Bell Tower and Drum Tower (Bell on the left, Drum on the right)
Structural System	1. Timber post-and-lintel or frame structure with purlins supported by columns 2. Brackets for load-bearing: Wudian roof (highest), Xieshan roof, Yingshan roof (common in folk temples)
Grading System for Cultural Relics	National/Provincial/Municipal-level cultural relics protection units, meeting the criteria of "historical, artistic, and scientific value"
Restoration Technical Norms	1. Following the principle of "no change to the original status of cultural relics" 2. Priority for traditional craftsmanship, e.g., mortise-tenon repair instead of iron nails for timber structures
Traditional Management Systems	Buddhist jungle system (three-level management: abbot, supervisor, weina)

are frequently used and have public attributes. The open spatial layout is conducive to flexible response and mitigation of disasters.

Data sources

This study primarily involves geoenvironmental data, spatial data and historical data. The geoenvironmental data includes the 2023 China National DEM (Digital Elevation Model), which provides elevation data with a 30-m resolution. This dataset was obtained from the Geospatial Data Cloud official website (<https://www.gscloud.cn/>) and is supplemented by the 2023 National Administrative Division Vector Map. Remote sensing images were processed using ArcGIS 10.2 to extract image data of ancient temples within the study area. The list of temples was obtained from the basic information registered by the State Administration for Religious Affairs (<https://www.sara.gov.cn/>) regarding religious venues.

There are a total of 238 temples registered in the study area that are still maintaining normal activities. As the research subject TT has the uniqueness of preserving traditional architectural structure, traditional space, and historical continuity, it is necessary to screen the data by referring to the standards of TTs (Table 1)^{52,53}. First, we reviewed the historical records in local county Chronicles and compiled a list of 126 ancient temples from 9 AD to 1801^{54–57}. Then, based on the historical records of cultural site protection units and temple inscriptions, we excluded the temples that were significantly relocated, rebuilt, or had an area of less than 100m² from this list. During the on-site investigation, we conducted a questionnaire survey and interviews with monks, cultural relics protection units, and local residents on the theme of the disaster prevention adaptability of temples. A total

of 120 questionnaires were distributed, and 79 were finally retrieved. Eventually, 100 traditional temples with historical and disaster prevention significance in the Longmenshan area of Sichuan Province were selected. Most of these temples can be traced back to the construction dates of the Sui and Tang Dynasties and the Ming Dynasty. We have drawn a time distribution map of the TTs (Fig. 3).

Through the annual work report on the rescue and protection of cultural heritage following the Wenchuan earthquake in Sichuan, other relevant materials, and 2-year on-site investigations, we acquired statistical data regarding the number of casualties in temples, the damage status of buildings, and the building renovation scenarios (Supplementary Table 1).

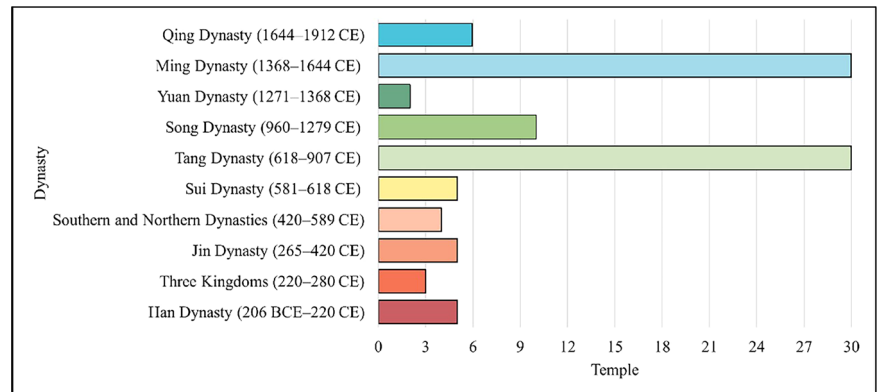
Spatial layout of TT

To characterize the spatial distribution of TTs and examine the influence of topographic heterogeneity on their siting patterns, this study applies Exploratory Spatial Data Analysis (ESDA) and geospatial modeling techniques are then employed to quantitatively analyze the relationship between physiographic elements and the distribution of these religious structures.

(1) Use ArcGIS to extract topographical data. using the nearest neighbor index, which is a geographical indicator to reveal the degree of proximity of point elements within a spatial scope:

$$ANN = 2 \sum_{i=1}^n d_i \cdot \sqrt{\frac{n}{A}} \quad (1)$$

Fig. 3 | Period diagram of traditional temples in Longmen Mountain area, Sichuan Province.



Where d_i is the actual nearest neighbor distance; n is the number of temple points; A is the area of the region. When $ANN > 1$, the TTs are discretely distributed within the region; when $ANN < 1$, the TTs are clustered; when $ANN = 1$, the TTs are randomly distributed.

- (2) Taking into account the combined effects of elevation and slope, With the help of the theory of topographic position index in land science⁵⁸ is utilized to comprehensively assess these factors. This approach allows a quantified assessment of the distribution of temple layouts and spatial forms under different terrain conditions. The topographic position formula is as follows:

$$T = \log \left[\left(\frac{E}{\bar{E}} + 1 \right) \times \left(\frac{S}{\bar{S}} + 1 \right) \right] \quad (2)$$

In the formula, T represents the topographic position index, E is the elevation of a specific temple point, \bar{E} is the average elevation of all temple points within the study area, S is the slope at a specific temple point, and \bar{S} is the average slope of all temple points within the study area.

A curve fitting calculation method was employed to compute the topographic position indices for each temple site, resulting in a statistical table of quantitative indicators for factors affecting temple layouts in the Longmen Mountain area of Sichuan (Supplementary Table 2).

Spatial morphology of TT

Using the indicators in the Landscape Pattern Index model, the spatial patterns and changes of the temple can be summarized quantitatively. The indicators of the Landscape Pattern Index are divided into four groups: area indicators, density size and difference indicators, edge indicators and form indicators. According to the research needs and the contrast of the landscape pattern index indicators, this paper selects the area of collocation type (CA), the number of collocations (NP) and the shape coefficient (LSI) to describe the morphology relationship between the buildings and the internal constituent elements of the temple space.

- (1) CA. Taking 100 temples as samples for the study, satellite maps of the temples were visually interpreted to establish layers based on the temple buildings, enclosure walls, pagodas, corridor steps, and other features. The building blocks were delineated using the boundaries of the building monoliths as contours. Subsequently, a general temple plan was created by outlining the periphery of the temple complexes. The area of the temple buildings was then statistically calculated using the following formula:

$$CA = \sum_{i=1}^n \alpha_{ij} / 10,000 \quad (3)$$

Where n is the number of patches contained in landscape type j ; α_{ij} is the area of the i th patch in landscape type j . The unit of the grid area is m^2 . For the convenience of calculation, we divide the result by 10,000 and convert it to ha.

- (2) NP. To quantitatively compare the proportions of emergency refuge areas and emergency evacuation channels within the open spaces of each temple, this study calculates these areas and their quantities as ratios of the total open space area, using actual measurements from each temple as the metric.

$$\alpha = \sum_i^n = \beta_i \times \frac{S_i}{\sum_i S_i} \quad (4)$$

$$\delta = 1 - \alpha \quad (5)$$

Where α is the average space proportion of emergency shelters; n is the number of emergency shelters; β_i is the space area of emergency refuge, S_i is temple i 's Open space footprint, $\alpha \in [0, 1]$, $\delta \in [0, 1]$.

- (3) LSI. Describes the shape characteristics of the entire landscape patchwork, with increasing values of the shape coefficient representing a more irregular shape of the patch, calculated as:

$$LSI = \frac{P}{2\sqrt{\pi A}} \quad (6)$$

Where P is the total length of all patch boundaries of the temple and A is the total area of the temple.

Identify the disaster prevention space

Disaster prevention spaces are defined as physical spaces within urban areas that possess functions such as disaster prediction, prevention, protection, and avoidance, as well as non-material spatial structures that meet the needs of disaster prevention⁵⁹. In the aftermath of significant natural disasters, individuals naturally congregate in open spaces such as parks and green areas to address urgent needs for evacuation, medical assistance, and food^{60–62}. The area and service radius classifications of urban disaster space standards are presented in Table 2. Combined with the requirement of more than 1 m^2 per capita evacuation area for places of refuge, as stipulated by the Urban Earthquake Prevention and Mitigation Planning Standards, we can categorize and assess different types of open spaces⁶³.

Temples represent a crucial type of disaster prevention open space, serving as dual-purpose public spaces for both everyday use and emergencies⁶⁴. These spaces can compensate for the shortage of shelters and enhance the equity of disaster mitigation for residents. The internal open spaces of temples offer flexible options for disaster prevention and relief efforts. Therefore, this study analyzes the distribution, location, and forms of disaster prevention spaces in temples to provide a theoretical foundation for examining their disaster prevention capacities⁶⁵.

This study focused on temples that serve community-wide areas, with research centered on regions prone to multiple hazards. In this context, disaster prevention spaces are defined as areas within the boundaries of temple complexes, including courtyards, gardens, and other physical spatial

elements. These spaces also accommodate activities such as recreation, worship, and evacuation, collectively forming specialized areas for refuge and disaster response. Considering that temples, on average, accommodate approximately 100 people per day, including visitors and staff, this study defines the area range of temple disaster prevention spaces as 100–4000 m². This facilitates the extraction of vector images and spatial data for these areas.

Calculation of the disaster prevention space of TT

By adapting the formula used to study the ratio of open space area to building area in urban environments, the ratio of the disaster prevention space area to the total occupied area of each temple is measured through actual measurements. This ratio serves as an indicator of the disaster adaptability of the temple's spatial design. The formula for the temple disaster prevention space area ratio is as follows:

$$OSR = \sum_i^n = j_i \times \frac{m_i}{\sum m_i} \quad (7)$$

Where OSR is the average proportion of OS; n is the number of OS; j_i is the area of the OS; m_i is the total occupied area of TT, $OSR \in [0, 1]$.

Quantitative indicators for influencing TTs layout

Due to the obscure patterns and limited quantity of data selected in this study, grey relational analysis, which requires minimal conditions for sample data (sample size > 4), was employed. Initially, the OSR in Buddhist temples was established as the reference sequence to reflect the spatial layout and disaster adaptability of these temples. The indices of natural disaster environments, represented by elevation, slope, and topographic position index, were used as comparative sequences to assess the disaster adaptability of the temples, leading to the creation of the original data matrix.

The average correlation coefficients for elevation, slope, and the topographic position index with the open space area ratio were calculated to be 0.6949, 0.4786, and 0.8107, respectively. These results indicate that elevation, slope, and the topographic position index all have moderate to high correlations with the open space area ratio, with the topographic position index demonstrating the highest correlation and slope the lowest. Each

factor significantly impacts the disaster adaptability of temples, albeit to varying extents.

Calculation of quantitative indicators affecting temple morphology

To effectively assess the disaster adaptability of Buddhist temples, establishing a set of quantitative indicators is crucial. The OSR of temples is selected as the reference series to reflect their disaster adaptability. The comparative series includes the temple's architectural scale, number of open space patches, and shape coefficient. Initially, a raw matrix is created and subsequently standardized to facilitate analysis. The next step involves calculating the correlation among these indicators by assessing the differences between the comparative and reference series. Finally, the correlation coefficients for each indicator are calculated, offering insights into their impact on the temples' disaster adaptability (Supplementary Table 3).

Results

Site selection characteristics

Terrain is a crucial natural geographical condition for the formation of temples. It not only provides space for their development but also acts as a limiting factor in their spatial distribution. Elevation, slope, and aspect are critical factors in disaster prevention, influencing the temples' access to sunlight, temperature, and availability of surrounding material resources. (1) Elevation characteristics: Different elevations provide varied material and climatic conditions, which influence the lifestyles and housing construction methods of temple communities and surrounding residents. Within the study, 77% of temples are located at elevations ranging from 400 to 1000 m, 21% are situated between 1000 m and 2000 m, and only two temples exist above 2000 m. There is a general negative correlation between elevation and the number of temples, indicating fewer temples at higher elevations (Fig. 4). (2) Slope characteristics: Considering the suitability for human habitation, temple slopes are categorized as follows: $\leq 8^\circ$ (very suitable), 8° – 15° (suitable), 15° – 25° (appropriate), and $> 25^\circ$ (unsuitable). In this study, 66% of temples fall into the “very suitable” category, 32% are in the “suitable” range, and no temples are found in the “unsuitable” range (Fig. 5). Overall, temples are predominantly located in the Chengdu Plain and tend to avoid areas with steep slopes, demonstrating a preference for gentler inclines.

Site selection classification

Based on the micro-geomorphology of the temple locations, TT in the study area is categorized into five distinct types: flatland, mountaintop, hillside, foothill, and mountain hollow. This study summarizes the findings from extensive field research (Fig. 6). (1) Flatland temples (34 in total) are primarily located in urban and suburban areas, characterized by relatively simple terrain. (2) Mountaintop temples (13 in total) are situated at

Table 2 | Urban disaster prevention and open space standard

	Radius of service/m ²	Walking distance/min	Minimal area/hm ²
Proximity	500	10	0.1
Regional	1000–2000	60	1
Central	2000–3000	120	50

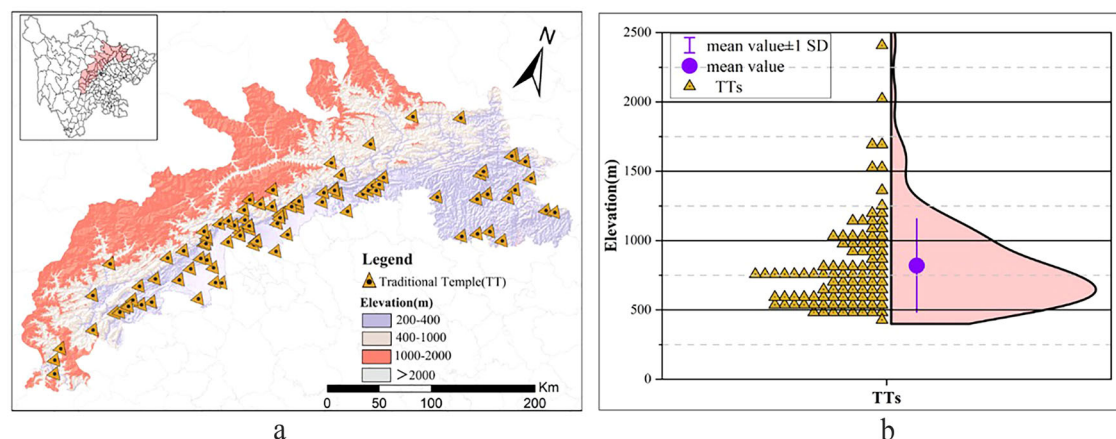


Fig. 4 | TTs Elevation Analysis Map. a TT's elevation distribution map, **b** TT's elevation distribution difference.

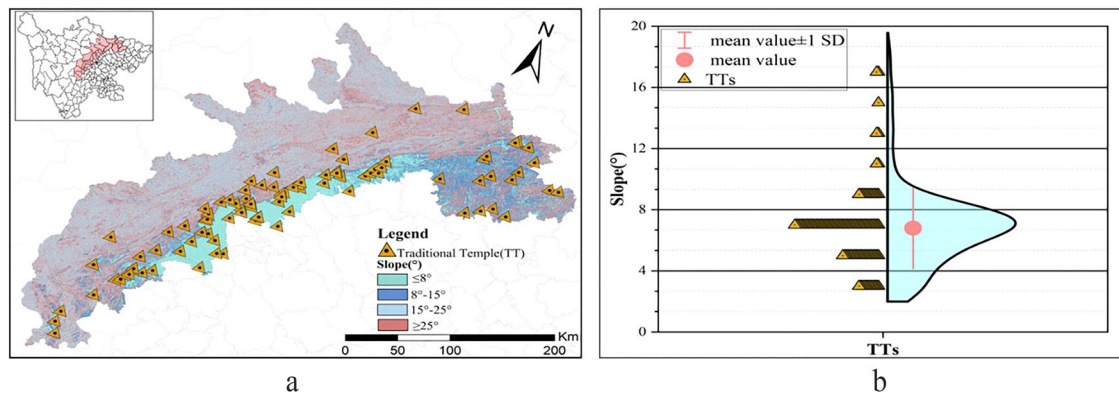
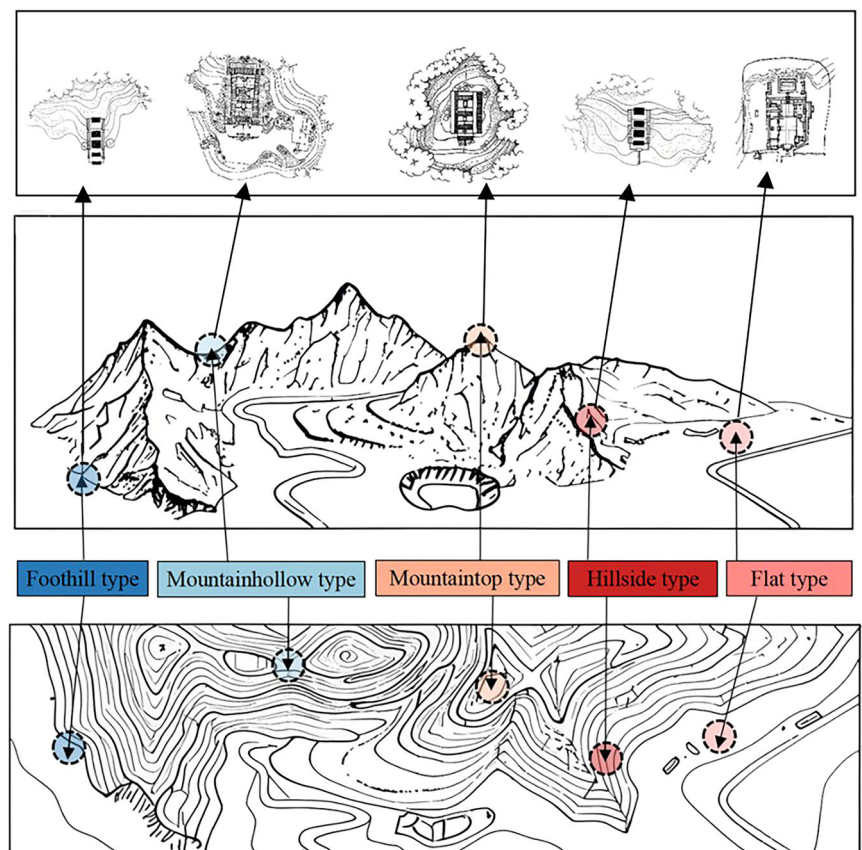


Fig. 5 | TTs slope analysis map. a TT's slope distribution map, **b** TT's slope distribution difference.

Fig. 6 | Type and characteristics of TTs in the study area. In the figure, the dark blue circle indicates the position of the foothill type TT, the light blue circle indicates the position of the mountain hollow type TT, the orange circle indicates the position of the mountaintop type TT, the red indicates the position of the hillside type TT circle, and the pink circle indicates the position of the flat type TT.



mountain summits, featuring intact spatial structures and elevated, flat terrain. (3) Hillside temples (24 in total) are typically located between the mountaintops and the foothills, often found in areas with steep slopes or mid-mountain terraces. (4) Mountain hollow temples (17 in total) are positioned on mountain plateaus or saddle areas, where the terrain differences are relatively minor. (5) Foothill temples (12 in total) are situated on the gentler slopes of mountains. The axial development of these temples typically follows two patterns: first, a linear distribution ascending from the base, marked by more dispersed temple layouts and greater changes in slope and elevation; second, a clustered distribution extending from the base onto flat land, where slope variations and internal elevation differences are relatively smaller.

Analysis of the disaster adaptability of site selection factor

The distribution of disaster-preventive space across various elevations is a key indicator of a temple's adaptability to disasters. A Pearson correlation

coefficient test revealed a strong correlation of 0.877 between the disaster-preventive space ratio and elevation. This strong correlation highlights the significant relationship between elevation and the allocation of disaster prevention in temple designs. Regression analysis indicates that the overall disaster-preventive space ratio for temples is 36%. Among the 94 temples located below 1500 m, the ratio is 34.6%, whereas six temples situated above 1500 m exhibit a ratio of 54%. The proportion of open space increases with elevation, exhibiting a clear linear upward trend (Fig. 7a).

Historical earthquake research suggests that sloped terrains amplify seismic responses⁶⁶, with steeper slopes experiencing greater impacts from geological disasters and posing increased challenges for disaster avoidance. Slopes in the Longmen Mountain area were categorized at 10° intervals, revealing that the 20°–50° range represents a concentrated disaster zone. Analysis of OSR at different slopes revealed a significant correlation of 0.796 between open space ratio and slope. All temples in the study area are located on slopes range from 0° to 20°. Within the 0°–10° slope range, the probability

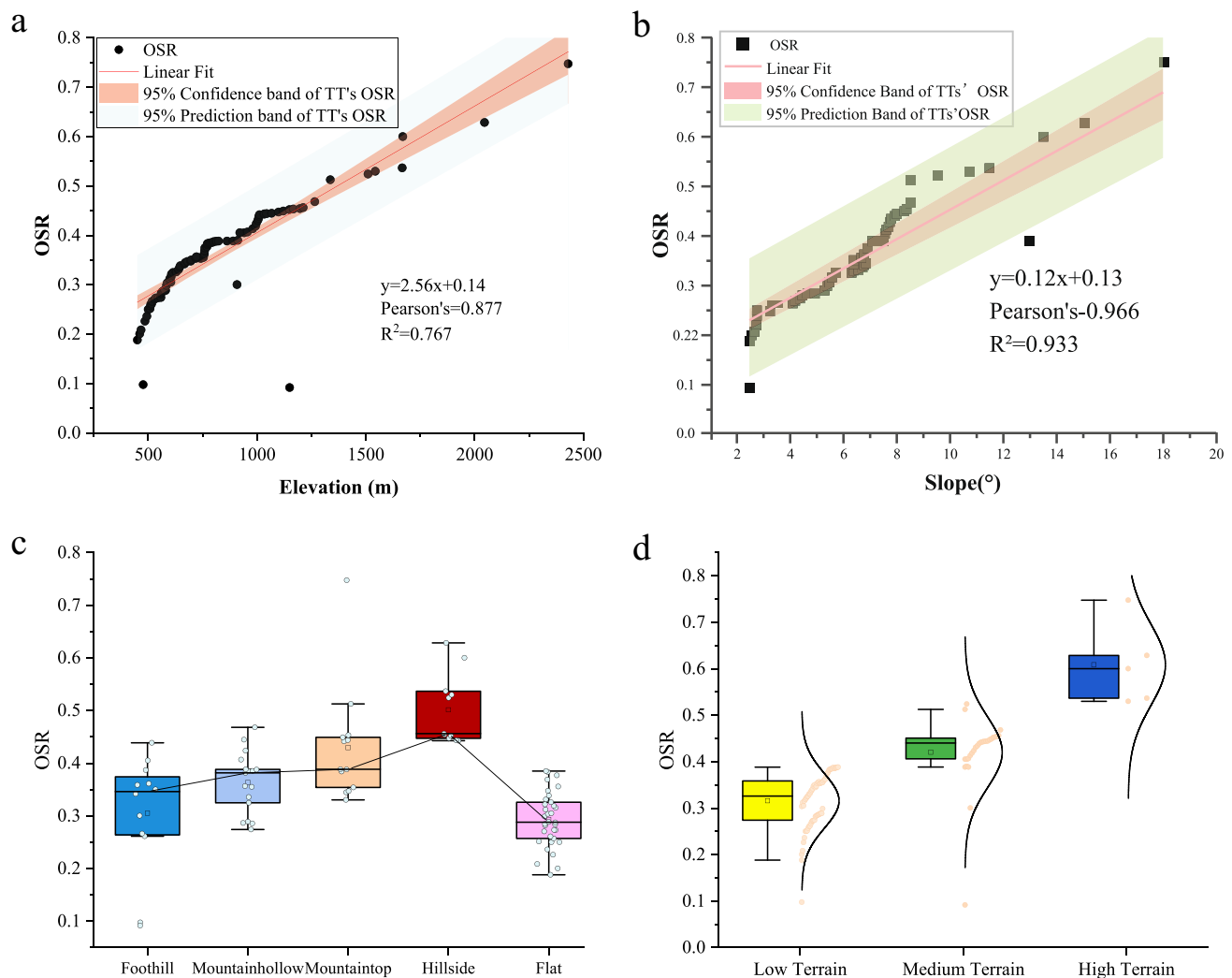


Fig. 7 | TT disaster prevention adaptability site selection analysis diagram.

a Comparison of TTs'OSR at different altitudes. In this graph, the black dots represent the OSR of TTs, the red line represents the linear fitting results, the pink range is the distribution range of the 95% confidence interval of TT, and the light blue range is the range of the 95% prediction interval of TT. **b** Comparison of TTs'OSR with different slopes. In this graph, the black squares represent the OSR of TTs, the red lines represent the linear fitting results, the pink range is the distribution

range of the TT 95% confidence interval, and the light green range is the range of the TT 95% prediction interval. **c** Comparison of TTs'OSR with different site types. In the figure, the dark blue indicates the position of the foothill type TT, the light blue indicates the position of the mountain hollow type TT, the orange indicates the position of the mountaintop type TT, the red indicates the position of the hillside type TT and the pink circle indicates the position of the flat type TT. **d** Comparison of TTs'OSR with different terrain positions.

of disasters is lower, with 93 temples exhibiting a OSR of 34.28%. In the 10°–20° slope range, where the disaster probability is approximately 12%, 7 temples exhibit an OSR of 58.27%. As the slope increases, the proportion of open space in temples increases gradually. (Fig. 7b)

The comparison of OSR across various temple site selections and their influencing factors yielded the following results: 34 flatland temples exhibited a ratio of 29%; 24 hillside temples, 44%; 17 mountain hollow temples, 36%; 13 mountaintop temples, 43%; and 12 foothill temples, 31% (Fig. 7c).

Terrain position. The terrain position index from land use science comprehensively describes the combined effects of temple open space, elevation, and slope. Multivariate linear regression analysis categorizes terrain position data from low to high using the natural breaks method as follows: low terrain position (0.26–0.63) corresponds to areas with simple, flat terrain; medium terrain position (0.63–1.18) to areas with noticeable undulations; high terrain position (1.18–2.17) to areas with significant undulations and construction challenges. The results indicate that temples in high terrain positions exhibit an OSR four times larger than those in low terrain positions. This suggests that temples in high terrain positions can

significantly increase open space during site selection to mitigate challenges in disaster relief (Fig. 7d).

Morphological characteristics

Temple complexes have evolved complex spatial mechanisms influenced by external conditions such as temple layout, functions, and construction era. These complexes can be categorized into natural green spaces, garden spaces, outdoor worship spaces, and corridor spaces, each serving as disaster refuge areas and evacuation routes (Fig. 8).

A temple green space is a large outdoor area within the temple. It has only low structures, open areas, tall trees and shelters. The natural green space of a temple is used as the temple landscape, release area for plants and animals. The natural green space occupies a large area of the temple and is mainly square or rectangular. Most of the space is in the temple doorway, near the open areas. The main entrances and exits are wide. Temple garden space refers to the outdoor public tour area of a temple after its transformation. The overall spatial scale of the temple is large, primarily based on a rectangular form with a symmetrical central axis. Spatially, it is located between the mountain gate and the main hall in most cases.

Worship space is an essential component of temples and can be categorized into indoor and outdoor areas. The indoor worship space consists of temple halls, which include the Buddha statue, Buddha symbols, kneeling areas, and offering areas. In contrast, the outdoor worship space encompasses kneeling areas, stupa pilgrimage areas, incense-burning areas, and offering areas located outside the main entrances and exits of the temple halls. The outdoor worship space is primarily composed of hard landscapes and serves as the longest and widest area for visitors during their temple tour. Generally, there are no tall structures in the pilgrimage space, except for the Buddha statue and stupa. This highlights the significance of the outdoor pilgrimage space as a major component of the temple's open area, occupying the largest portion of the temple grounds. It is characterized by diverse shapes, strong axial mobility, and openness on all sides, with no defined entrances.

Corridor space functions as a transitional area that connects the various functional subdivisions of the temple. According to field

measurements, the width of pathways and corridors leading to the temple gate ranges from 1.3 to 1.6 m. This study includes these measurements in the analysis of temple corridor spaces. Typically, corridor space serves as a channel for temple activities and is not restricted to porches, passageways, or attraction patches. The area of the corridor space is relatively small, with stone slabs and stones being the predominant construction materials (Table 2).

Morphological classification

Based on field sketches and remote sensing image analysis, three typical temple morphologies are identified according to the number, location, form, area, and type of various spatial components within the temples: **axial symmetry**, **central isolation**, and **multi-axial dispersion** (Table 3). In the study area, 44 TT exhibit axial symmetry, constituting the majority among flatland temples. Typically, there are two main OS, which are easily accessible from all major and auxiliary halls, making this layout suitable for temples with traditional designs. The OS in these temples is organized along multiple directions and axes, featuring point-like distributions around various temple areas. This layout is particularly suited for temples with dispersed architectural designs, lacking a clear sequence. It facilitates quick evacuation and allows for flexible use of space in emergency situations. These temples typically feature one large OS, generally situated in elevated mountainous areas. Although bordered by buildings on two or one side, the axis is often incomplete (Table 4).

Analysis of the disaster adaptability of morphological influencing factors

The architectural scale of temples within the study area varies significantly. By overlaying data on OSR to CA, a strong correlation was identified, with a grey relational degree of 0.797 between the OSR and CA. Subsequently, a regression model was constructed to analyze the relationship between architectural scale and the OSR. The results indicate that the OSR generally decreases as the architectural scale increases, demonstrating a linear downward trend (Fig. 9a). The Landscape Shape Index (LSI) was calculated and averaged for the three morphological types of temples, yielding the following results: Axial symmetry type: LSI at 1.93. Multi-axial dispersion type: LSI at 2.03. Central isolation type: LSI at 1.46. These results suggest that

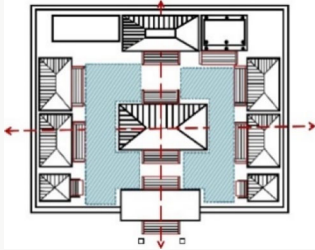
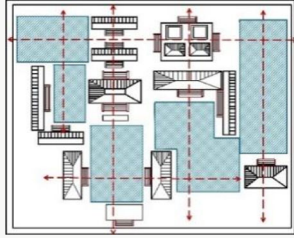
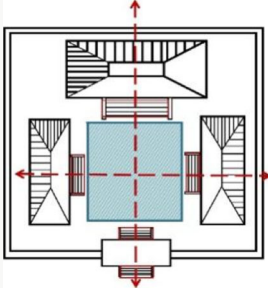
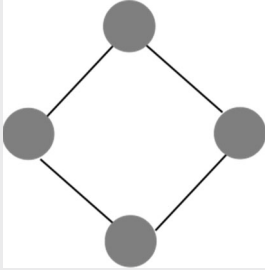
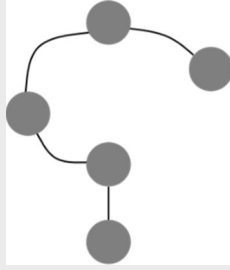
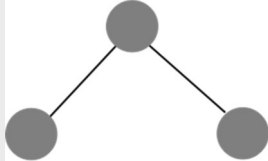


Fig. 8 | Map of the open space distribution of the TT. In the picture, the yellow circles represent green spaces, the blue circles represent garden spaces, the purple circles represent worship space, and the green circles represent corridor spaces.

Table 3 | Statistical plots of TT's open spaces

	Green spaces	Garden space	Worship space	Corridor space
Plan				
Scene				

Table 4 | The morphological types and characteristics of TT’s in the study area

Morphotype	Axial symmetry	Multi-axial dispersion	Central isolation
Sketch Map			
Topology diagram			

traditional, simple spatial structures increase the ratio of open space in temples. In contrast, dispersed structures with multiple exits and routes enhance both the quantity and layout of open spaces in temples (Fig. 9b, c).

The disaster risks of TT

Although it is generally believed that the traditional wooden structure TT can dissipate seismic energy and has good seismic resistance, due to its long service life, material aging, and other reasons, TT still poses risks such as building collapse⁶⁷. Through an on-site investigation of TT in the study area, it was found that the potential disaster risks of TT in different building structures vary^{47,68}.

(1) Wooden structure TT: Most wooden structures suffer minor seismic damage, but there is a risk of mild seismic damage, such as falling tiles, small-distance sliding of column bases, and damage to local mortise and tenon joints. (2) Stone-wood structure TT: The seismic performance of stone-wood structures is slightly inferior. The force-bearing strength of stone columns and wooden beams is different, and there is a potential risk of cracking of wooden beams and breaking of the roof ridges. (3) Brick-wood structure TT: When the wall thickness of a brick-wood structure is relatively thin, there is a risk of the building collapsing. (4) Reinforced concrete frame imitation wood structure TT: The building’s “displacement capacity” is relatively low, and the risk of wall collapse and building collapse is high (Fig. 10).

Overall, the risk of damage to wooden structures is relatively low. Stone-wood structures and brick-wood structures were slightly inferior, while reinforced concrete frame imitation wood structures suffered more severely. Newly built or expanded mixed structures were severely damaged.

Disaster prevention status of other shelters

Based mainly on the information of large-scale shelters officially released, by collecting and analyzing the geographical and spatial data of large-scale shelters within the region (Supplementary Table 4), it can be found that (1) Altitude characteristics: Similar to temples, the distribution of official large-scale shelters B is generally negatively correlated with altitude. About 80% of other shelters are located within the altitude range of 400–1000 m, and 17% are within the range of 1000–2000 m. However, the difference is that official shelters are not entirely restricted by altitude or slope. More of them are distributed in areas where large earthquakes have occurred. Two clustering points have emerged, namely the Ya an area and the urban area of Pengzhou

(Fig. 11). (2) Slope characteristics: Considering suitability for human habitation, slopes are classified as $\leq 8^\circ$ (very suitable), $8^\circ\text{--}15^\circ$ (relatively suitable), $15^\circ\text{--}25^\circ$ (suitable), and $>25^\circ$ (unsuitable). In this study, 61% of the official large-scale shelters were classified as “very suitable”, 27% were in the “relatively suitable” range, 7% were in the “appropriate” range, and 6 shelters were in the “inappropriate” range (Fig. 12). (3) Spatial design features: The spatial design of large-scale shelters can be classified into five types: school type, square type, park type, professional shelter type, and government agency land type. There is no uniform standard for the form of refuge space in each type of place. Instead, it is designed with the goal of accommodating the number of people. Therefore, when calculating the form of space, we calculate the OSR of each type of large refuge space based on the proportion of 1.5 m^2 . The results obtained are professional refuge OSR > square OSR > park OSR > government agency OSR > school OSR (Fig. 13).

A comparison of disaster prevention between TT and other shelters

From the analysis of layout characteristics, although the overall distribution of TT and modern shelters both shows a trend of low altitude and gentle slopes, the concentration points of modern shelters are mainly found in the urban areas of Ya an City and Shifang City, which have experienced major earthquakes before. TT, on the other hand, has a clustering pattern throughout the region, especially with many TTs located in mountainous areas. It fills the gap in the distribution of modern shelters in high-altitude mountainous areas and enhances the fairness of disaster prevention. From the perspective of spatial form analysis, both have their own design features. TT is influenced by traditional Chinese architectural styles. Its spatial design is based on the axis, and there must be large areas of open gardens and green Spaces within the enclosed space of the building to continue the texture of the space. The building materials are mainly lightweight wood and stone columns, and most of the building structures are mortise and tenon structures. Therefore, when TT is threatened by disasters such as earthquakes, its unique traditional architecture can absorb part of the seismic stress, reduce losses, and the open Spaces inside can serve as emergency shelters for local residents. Modern shelters adopt modern seismic technical standards and new seismic materials, which can more effectively ensure the stability of the buildings. Open Spaces are mostly designed according to the number of people they can accommodate and have no fixed form⁶⁹.

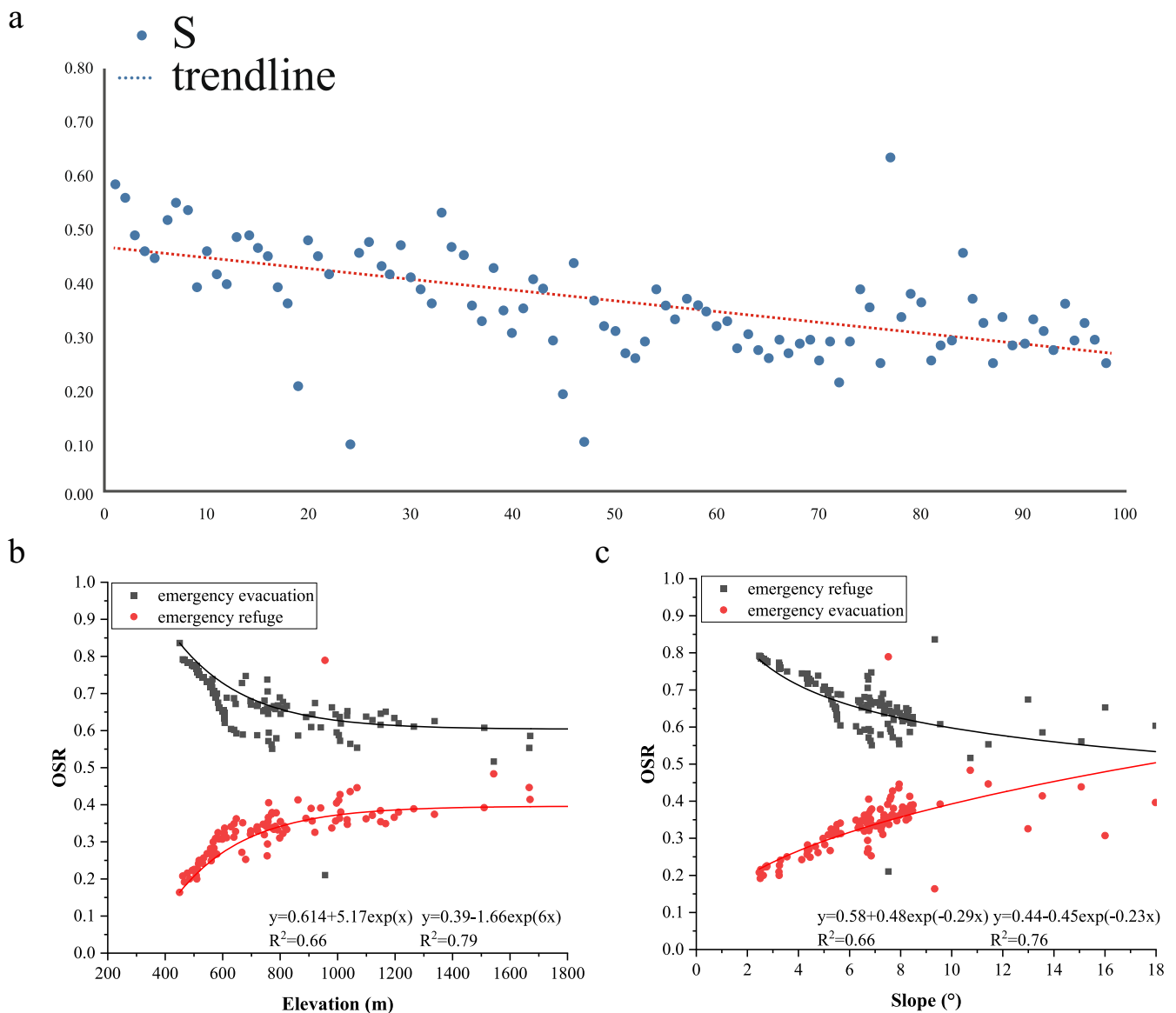
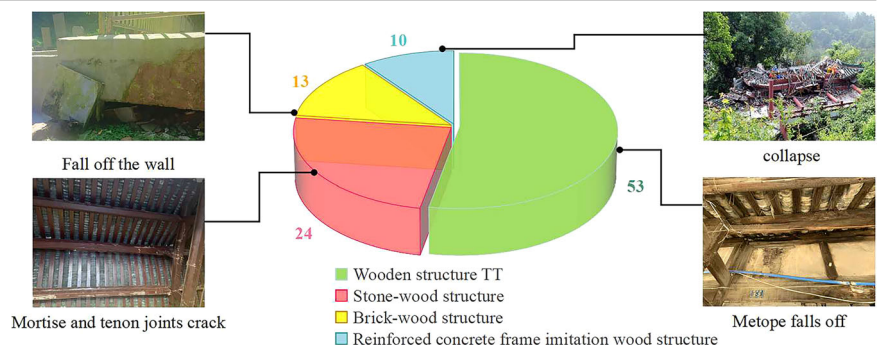


Fig. 9 | Morphological analysis diagram of TT disaster prevention adaptability. **a** Relationship between TTs' building scale and space area ratio. In this diagram, the horizontal axis represents the building scale of TTs, and the vertical axis represents the OSR of TTs. **b** Functional elevation distribution of TTs' open space. In this picture, the red dots represent the area of emergency refuge and the gray squares

represent the area of emergency evacuation. The horizontal axis represents altitude, and the vertical axis represents the proportion of area. **c** Functional slope distribution of TTs' open space. In this picture, the red dots represent the area of emergency refuge, and the gray squares represent the area of emergency evacuation. The horizontal axis represents slope, and the vertical axis represents the proportion of area.

Fig. 10 | TT risk analysis. In the figure, green represents wooden structure TT, red represents stone-wood structure TT, yellow represents brick-wood structure TT, and blue represents reinforced concrete frame imitation wood structure TT. The arrows point to the typical earthquake damage site diagrams of each type.



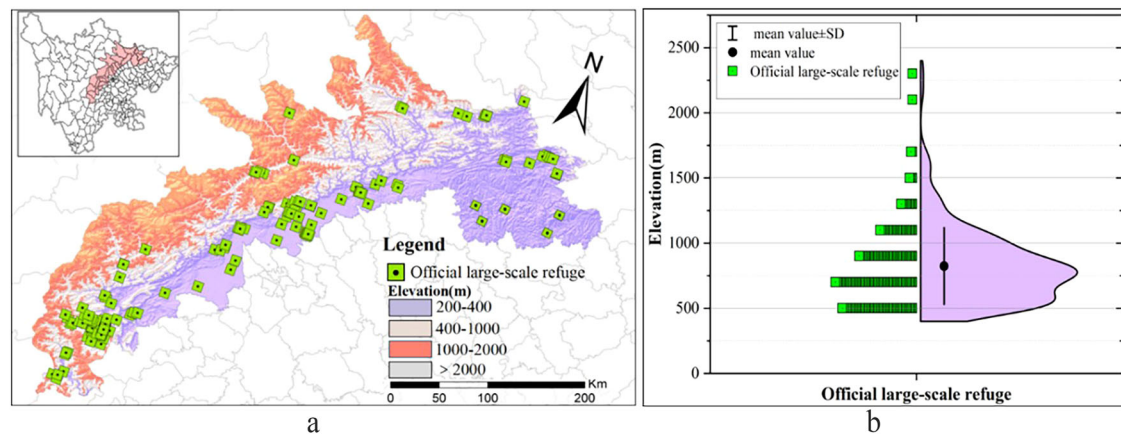


Fig. 11 | Official large-scale refuges elevation analysis map. **a** Official large-scale refuges elevation distribution map. In the picture, the green dots represent official large-scale refuges. **b** Official large-scale refuges elevation distribution difference.

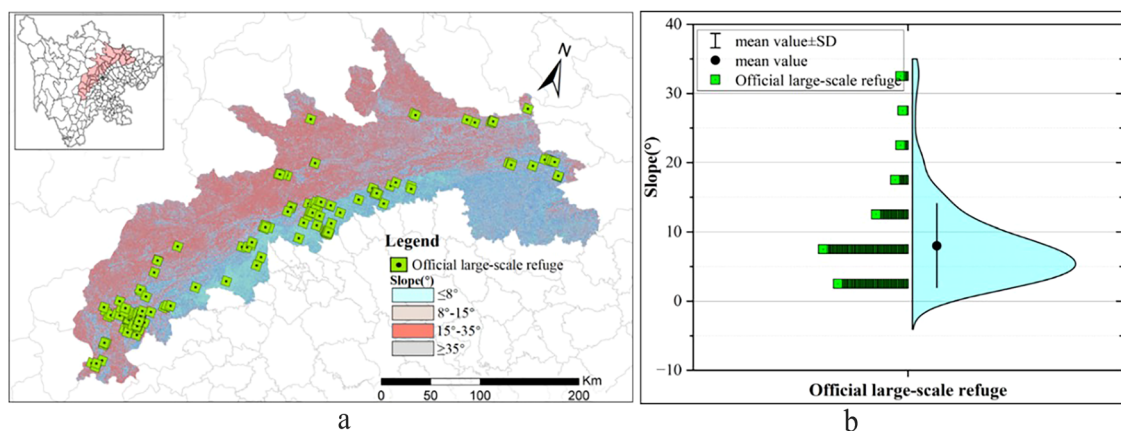


Fig. 12 | Official large-scale refuges slope Analysis Map. **a** Official large-scale refuges slope distribution map. In the picture, the green dots represent official large-scale refuges. **b** Official large-scale refuges slope distribution difference.

Discussion

This study aims to expand the role of temples beyond their traditional religious, environmental, and cultural functions to include their potential contributions to natural disaster mitigation. It focuses on the siting and spatial mechanisms that shape temples within the multi-hazard environment of the Longmen Mountains, where temples serve as public spaces with validated disaster prevention capabilities, particularly in the context of frequent earthquake events. Despite their potential, the role of religious sites in disaster risk reduction remains insufficiently explored in existing literature. This study seeks to address this gap by examining how temples can function as disaster-resilient spaces, integrating their traditional roles with innovative approaches to disaster mitigation.

After reviewing the Sichuan Provincial Cultural Relics Bureau's statistics on damage to various levels of cultural heritage protection units during the 5.12 earthquake, and following the author's two-year field surveys and research visits to the temples, a detailed survey table of the disaster conditions of temples was compiled (Table A3). During the 5.12 earthquake, over 60% of temples suffered minor damage, while only about 10% experienced severe damage, with almost no casualties reported. Evacuations were swift, and although incidents such as falling roof tiles and cracking non-load-bearing walls occurred, these were considered minor hazards. The absence of large-scale relocation or reconstruction not only validates the seismic resistance of the temple structures but also indirectly demonstrates the disaster adaptability of the temples' spatial layout and site selection^{47,48}. This survey also revealed that the damage to ordinary residential buildings

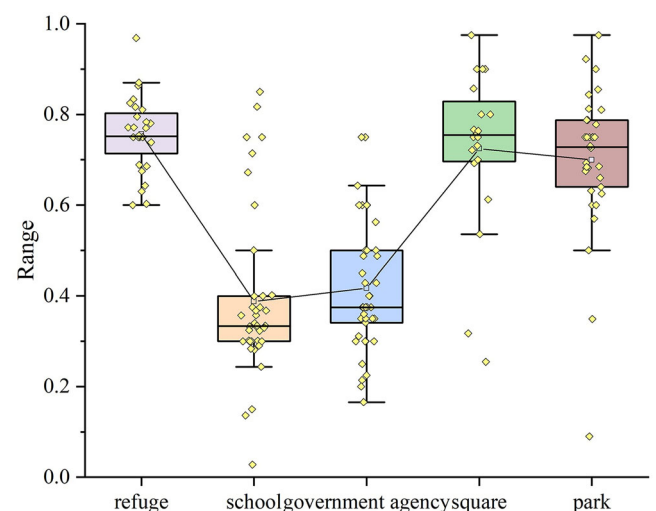


Fig. 13 | Official refuge sites of different spatial form types OSR. In the figure, purple represents refuge, orange represents school, blue represents government agency, green represents square and pink represents park. The horizontal axis represents the official refuge type, the vertical axis represents the OSR value, and the yellow dots represent all official refuge sites.

Fig. 14 | Comparison of damage to Han Buddhist temples and dwellings in Longmen Mountain, Sichuan. **a** Statistical chart of temple damage in the study area. **b** Statistical chart of damage to residential buildings in the study area. In the picture, green represents minor damage, yellow represents moderate damage, gray represents severe damage, and purple represents largely intact.

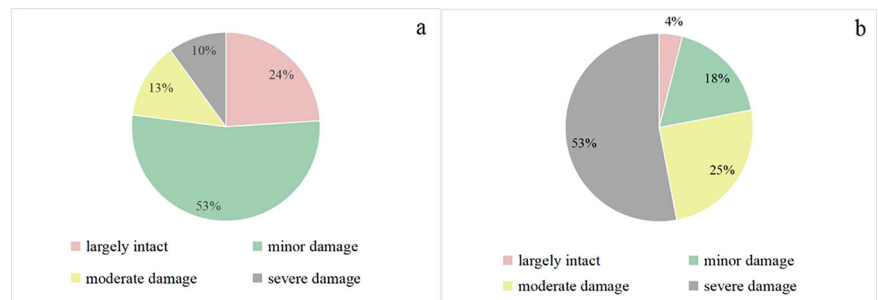
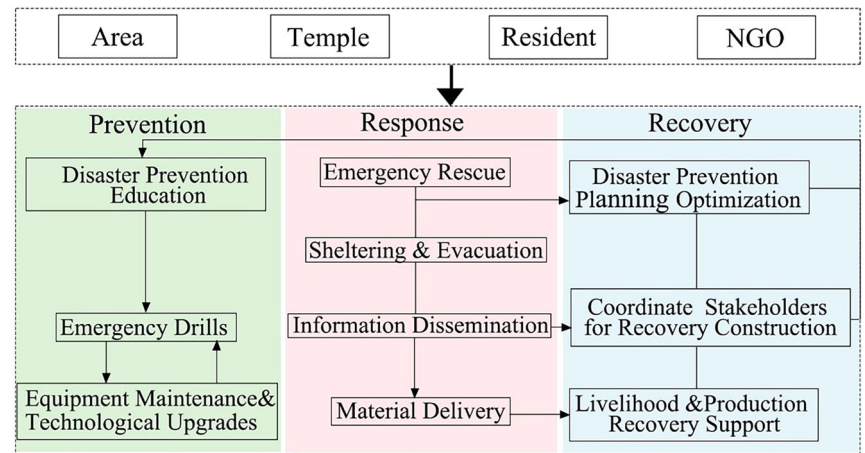


Fig. 15 | Diagram of the disaster prevention lifeline mechanism for temples.



was severe, with up to 53% being destroyed or severely damaged, while only 4% of the homes remained largely intact after the disaster^{70,71}. This result intuitively reflects the fact that the disaster resilience of Han Buddhist temples in the study area, as well as their adaptability to the disaster environment, far exceeds that of the ordinary residential houses in their vicinity (Fig. 14). These temples possess the necessary conditions and potential to serve as temporary refuges in the region (Fig. 15).

However, when large-scale disasters occur, due to the aging and historical wear and tear of traditional building materials, TT still faces potential risks such as building collapse. Therefore, the application of modern seismic resistance technologies and materials is conducive to enhancing TT's disaster prevention resilience. For instance, a disaster detection and early warning system is deployed in TT, optical fiber sensors are implanted in wooden components to monitor structural strain in real time⁷², low-power sensors are installed in key parts such as roofs and dougong brackets, and a three-dimensional vibration monitoring network is constructed to provide early warnings of earthquake disasters^{73,74}. In terms of building materials, the attempt to use nano-silica modified mortar can slow down the rate of wall cracking. The use of bionic bamboo joint wooden components can dissipate energy through plastic deformation at the nodes during earthquakes.

We found that the overall OSR increases with the elevation and slope of the temple distribution. This trend may be related to the engineering challenges associated with temple construction. As elevation and slope increase, the difficulty of building construction also rises, resulting in a naturally higher OSR compared to the percentage of buildings.

Most of the original sites of temples belong to two kinds. One is that temples choose their locations voluntarily to hide in mountains and rivers in order to satisfy the idea of "retreating from the world for practice and wandering through mountains and rivers". Due to the complex terrain of mountains, the available space is limited, and the construction activities aim at causing less human disturbance to the natural environment, so more open

space will be reserved. Another type of temple originates from the ancient practice of "serving as a temple," where temples were built on or expanded from the original sites of local officials' residences, gentry homes, or ancestral halls. They were directly situated within towns and villages, facilitating local residents' worship and rituals. Due to the high density of buildings around them, the temples lacked space to expand outward, so they increased their internal building space.

Adaptive planning for disaster prevention is a long-term and dynamic process^{35,36}. Given the varied, diverse, and complex nature of disasters faced by temples, it is essential to construct a lifeline system for disaster prevention within temple communities. This means that temples and disaster-stricken clusters can maintain the infrastructure network of basic community functions, such as transportation, communication, food and water sources, medical rescue, etc. This system should integrate temples, community residents, governmental organizations, and NGOs within the temple's area of influence into cohesive groups⁷⁵. A mutual aid lifeline system should be established for each group, ensuring that the disaster prevention plans of all groups are interconnected. This interconnected system would enable dynamic coordination and adaptability in disaster prevention efforts.

(1) When temples face disasters, they generally go through three stages: before the disaster, during the disaster, and after the disaster. In disaster prevention planning, the principle of comprehensive process should be upheld, which means from prevention and preparation before the disaster occurs, to emergency response during the disaster, and then to recovery and reconstruction after the disaster, forming a full-chain and systematic management framework to enhance the overall capacity for disaster prevention and mitigation. Before a disaster, it is necessary to carry out a risk assessment, formulate emergency plans, build disaster prevention facilities, and conduct public disaster prevention education. Quickly activate the emergency mechanism during the disaster, evacuate and escape, and carry out emergency rescue. After a disaster,

- conduct a disaster damage assessment and repair and optimize disaster prevention facilities. The combination of the three ensures the flexibility of the planning scheme.
- (2) The disaster adaptation planning for temples should focus on the long-term and dynamic nature of traditional ancient temple renovations. Disaster prevention for temples is not just about constructing disaster-resistant buildings or installing disaster facilities; it is essential to recognize that the renovation of traditional ancient temples is a long-term project, not a short-term achievement. The disasters faced by temples are diverse and complex, so it is necessary to establish a lifeline system for temple disaster prevention. All temples, community residents, grassroots government organizations, and NGOs within the affected area should be unified into various groups, establishing a mutual aid lifeline system within each group. Each group's disaster prevention plan should have interconnectivity, thereby creating a dynamic and adaptable disaster prevention lifeline system. This will facilitate rescue and mutual assistance, material supply, personnel rescue, and post-disaster recovery between groups. The goal is to maximize the stability of the group system, minimize disaster impacts, and reduce the reconstruction period after disasters.
 - (3) When a temple is hit by disasters, it needs to immediately utilize effective disaster prevention facilities within the space to respond to the disaster and carry out emergency rescue operations, as well as disaster reconstruction. Taking Sanxi Temple as an example, during the 2008 earthquake and the 2012 temple fire, the internal evacuation routes and fire prevention facilities played a crucial role. Focusing on the intersection of the main building's connecting passages, water tanks and other fire prevention facilities were installed, and prominent signs indicating the primary disaster prevention responsibility for each building were set up on visible walls, pinpointing individuals and conducting regular disaster prevention education activities for these responsible persons; internal evacuation routes connect green spaces and open areas in all directions of the temple, meeting the principle of combining peacetime and disaster response. This principle means that the infrastructure, spatial layout and resource allocation of the temple can take into account both daily usage needs and disaster emergency functions, achieving "one set of facilities, two uses".

The findings aim to offer a traditional construction theory reference for future spatial morphology and disaster prevention planning in residential environments within disaster-prone areas. The main conclusions are as follows:

- (1) From a macroscopic perspective, the distribution of temples in the study area is relatively concentrated, favoring low altitude, gentle slopes, and sunny directions, reflecting the characteristics of a region far from the threat of disasters. According to the topography, the layout of temples in the study area can be divided into four types: 1. Flat type. Mountaintop type 3. Hillside type 4. Mountain hollow type 5. Foothill type. On the other hand, official shelters are mainly concentrated in the areas that were once severely affected by earthquakes, with an uneven distribution. Temples can fill in the blank areas.
- (2) The topographic factors influencing temple layout and OS exhibit a strong correlation. As elevation and slope increase, the OSR within temple grounds also tends to rise. Moreover, the level of disaster risk in the study area is positively correlated with the topographic index. A higher open space ratio enhances the efficiency of evacuation and rescue operations in Han Buddhist temples during disaster scenarios, highlighting a notable degree of disaster adaptability in their spatial design. The OSR of official shelters is highly correlated with the nature of their construction. Among them, parks have the highest OSR, while schools have the lowest. The key lies in the number of people they can accommodate and the safety of the buildings, to highlight the disaster adaptability of the places.
- (3) The open spaces within temples serve two primary disaster prevention functions: 1. Evacuation routes, and 2. Places of refuge. The

mountain incense path and corridor spaces within temples connect the various functional divisions, serving as essential channels for the movement of people and the transport of materials. From a disaster prevention and mitigation perspective, the proportion of refuge areas is consistently greater than that of evacuation routes. A 65:35 ratio of refuge areas to evacuation routes significantly enhances the ability of ancient temples to adapt to disaster environments. When the altitude of the temple layout reaches 1000 m and the slope is 8°, the proportion of evacuation routes transitions from an increasing trend to a gradual decrease. Simultaneously, the proportion of refuge areas shifts from a decreasing trend to a gradual increase. This trend is similar to that of modern earthquake-resistant sites. Considering the difficulty of construction and the usage scenarios of personnel, modern earthquake-resistant sites will design the size of refuge buildings based on the number of people they can accommodate, and pay attention to the connection degree between evacuation passages and urban main roads.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

Dai and Zeng wrote the main paper; Di and Pei provided financial support for research and supervision, and review of paper production; Li and Chen assisted with the survey, collecting data for Survey Forms A1–A3; Nienkötter and Qiao prepared figures 7 and 9. All authors reviewed the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Baofeng Di.

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