Influences of a debris flow disaster chain on buildings in remote rural areas, Southwest China

Lu Zeng\textsuperscript{a,b}, Yonggang Ge\textsuperscript{a,b}, Jiangang Chen\textsuperscript{a,b}, Fenghuan Su\textsuperscript{a,b}, Huayong Chen\textsuperscript{a,b}, Wanyu Zhao\textsuperscript{a,c} and Guangwu Si\textsuperscript{a,c}

\textsuperscript{a}Key Laboratory of Mountain Hazards and Earth Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS), Chengdu, China; \textsuperscript{b}China–Pakistan Joint Research Center on Earth Sciences, CAS-HEC, Islamabad, Pakistan; \textsuperscript{c}University of Chinese Academy of Sciences, School of Engineering Science, Beijing, China

\textbf{ABSTRACT}

The magnitude and frequency of mountain hazards will continue to increase because of climate change especially in rural mountainous areas, which have not received much attention. In this article, a debris flow disaster chain in Southwest China caused damage to buildings along the river bank was investigated. The disaster chain included a debris flow, river blockage, lake formation, and an outbreak flood, and this study further investigated the disaster-related losses in downstream villages. Based on the characteristics of failed buildings, three structural types were identified, while the functions of undamaged buildings were affected by flooding or siltation by sediments. In addition, the building layout and riparian vegetation zone influenced the blockage effect, which resisted the flood impact and provided protection to rear buildings. Moreover, this disaster changed the river topography, the studied reach changed from a V shape to a wide–shallow shape, the appreciably affected river length was 6270 m, and the gully bed was noticeably raised 15–20 m. Furthermore, the flood control standard of a 50-year return period was recommended for reference, despite the limitations of these suggestions, we hope that this study attracts the attention of researchers on disaster prevention and mitigation in remote rural areas.

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\section{1. Introduction}

Extreme rainfall-induced floods are becoming more frequent and catastrophic (Masozera et al. 2007), and they are the most frequent natural hazard in the world, affecting the majority of countries on a regular basis (Merz et al. 2010). They can occur at any time of the year and are most often caused by heavy rainfall (Kundzewicz et al. 2020), rapid melting of a thick snow pack and ice jams (Ishida et al. 2019), or, more rarely, by the failure of human-made dams and natural
landslide dams (Butt et al. 2013; Liu et al. 2021). Floods account for almost 30% of the global losses associated with natural hazards (Petit-Boix et al. 2017) and affect not only developing but also developed countries; for instance, floods occur in developing countries, such as Bangladesh (Mondal et al. 2020), Thailand (Tabucanon et al. 2021), and India (Mohanty et al. 2020), as well as in developed countries, such as the United States (Hossain and Meng 2020) and Italy (Magliulo et al. 2021).

Postflood investigations contribute to future disaster management, and disaster losses are closely related to the flood characteristics, building geometry and material, and blocking effects among buildings. Buildings in rural mountainous areas are generally located along narrow strips of land on both banks of rivers, and masonry is the most common and frequently used building material (Kang and Kim 2016). Compared with urban buildings, masonry’s resistance to impact damage is very poor. The threat of mountain flash floods is directly related to the personal safety and property losses of residents (Ahmadalipour and Moradkhani 2019; Li et al. 2019; Diakakis et al. 2020). However, the design and construction of residential buildings usually lack unified planning and management, resulting in a variety of structural types and complex layouts. When disasters occur, their destruction methods are different for buildings with various structural forms. Therefore, it is of great significance to study the building destruction modes and disaster-causing mechanisms produced by floods. Physical scale model tests were carried out based on flood disasters in Schnanerbach, Austria, and the results presented a clear correlation between the approaching flow heights and the impact forces on exposed buildings (Sturm et al. 2018a, 2018b). The results also indicated that the impact force was closely related to the process of sediment transport and deposition and the spatial distribution of the buildings on the fan (Gems et al. 2016; Sturm et al. 2018a, 2018b). They also found that the layouts of the building groups showed a blockage effect and that openings in a wall greatly affected the impact force on a single building. The maximum impact force of a water–sediment mixture was 4.3 times that of clear water. An impact force calculation model combining the characteristics of building materials and hydrodynamic processes has been proposed (Tang and Hu 2018). However, the experimental findings still lack validation of prototype flood cases.

According to the statistics and assessment of 130 damaged buildings caused by flash floods in Braunsbach, Germany, in 2016, the degree of damage to buildings was related to their structural type and orientation, and the impact force and disaster-causing intensity were much higher for flash floods than for river floods because flash floods carry large amounts of solid debris (Maiwald and Schwarz 2016; Laudan et al. 2017). Based on the structural characteristics of masonry buildings in mountainous areas in Brescia, Italy, the failure mode of masonry walls under flood action was obtained by using finite element analysis, and the limit state equation of masonry walls under flood impact was established based on the virtual work principle (Milanesi et al. 2018). The flood impact on stilt houses in Thailand was analyzed by using numerical simulation; then, the vulnerable parts were determined, and structural reinforcement methods were proposed (Charoenchai and Bhaktikul 2020). According to the location and size of doors and windows in typical residential buildings in Malaysia, Faisal et al. (2018) proposed that the larger the opening is, the
smaller the flood impact load on the wall, and the damage to a building caused by a flood can be effectively reduced by optimizing the opening size, location, and combined style of walls. In addition, the elevation and distance from the river are considered the two most influential factors (Fernández and Lutz 2010; Tehrany et al. 2015). Higher elevations possess a lower risk of flooding, and lower elevations possess a higher risk of flooding (Cao et al. 2016).

Most previous flood studies have focussed on urban flooding (Mignot et al. 2019; Li et al. 2021); they have focussed on damage-related issues, such as submergence, soaking, and softening of foundations. However, flash floods have a powerful ability
to cause impact damage and burial damage to buildings, and little interest has been shown in floods in rural mountainous areas, which are related to the impact, erosion, and depositional effects of floods on buildings. Even the effect of damage on buildings and corresponding flood control standards in mountainous areas have been addressed in relatively few studies. Buildings in these areas present a high risk to local residents and their property but smaller economic losses. Recovery and reconstruction are more difficult for local residents. The research framework of this article is as follows: this discussed disaster chain involving a debris flow, river blockage, lake formation, and an outbreak flood, as well as the formation process and the impact of the disaster chain are first analyzed, and then the damage to downstream villages along the river due to the outbreak flood is determined. Thus, this article provides a characterization of the debris flow disaster chain that occurred on June 17, 2020, in Danba Figure 2. Damage of debris flow disaster in the Meilong gully.
County, China, and is based on data acquired during field work both immediately after the event and during subsequent months. The research aim of our study is to reveal the damage caused by mountain disasters to self-built buildings without design standards, to attract the attention of researchers on disasters in remote rural areas and to provide technical support for the future design standards and reasonable planning of village buildings.

2. Study area and method

2.1. Study area and disaster

The Meilong gully (102.03°E, 30.98°N) is located in Sichuan Province, Southwest China, 39.4 km southwest of Xiaojin County and 19.8 km northeast of Danba County, as shown in Figure 1. The Meilong gully is situated in the downstream reach and on the right bank of the Xiaojinchuan River (XJCR), and the elevations range from 2119 to 4439 m. The watershed area is 62.55 km², the length of the main gully is 10.8 km, and the mean slope of the gully is 25%. The original slope of the debris flow deposition area is 11.4%, and the mean width of the XJCR at the Meilong gully outlet is 26.8 m. Pre- and post-Meilong debris flow images show that the deposits cover the whole gully bottom, whose widths range from 20 to 80 m, and the total source material in the gully amounts to $84.8 \times 10^4$ m³. The highway along the XJCR is provincial highway No. S303. Many villages are scattered along the rivers and highways in this area, the population is concentrated in the gully alluvial-diluvial fan-shaped area and the narrow terraces along the river, and some villages are located in the middle part of the high mountainous area.

Due to long-lasting rainfall in this area, as shown in Figure 2, at 3 am local time (Beijing) on June 17, 2020, a short intense rainstorm occurred near Banshanmen town, Danba County, China. According to the regional meteorological record, the rainfall intensity reached that of a standard 50-year return period. The runoff intensely scoured the unconsolidated deposits that had accumulated in the gully bottom and triggered a debris flow event in the Meilong gully. Based on the description provided by local residents, the debris flow consisted of at least three main surges. This debris flow is important in that it is one of the largest debris flows to have occurred in this gully, and the Meilong gully is a low-frequency debris flow valley with numerous forested areas and villages present in the gully bottom. The debris flow travelled downstream at a high velocity along the entire gully length of 3.5 km. At the mouth of the Meilong gully, the debris flow entered the XJCR and dammed the river. The riverbed was elevated by approximately 8–12 m, a dammed lake formed, and the main river was compressed and shifted to the left bank. The outburst flooding process began at 12 pm and ended at 4 pm, and the maximum outburst flood discharge was 492 m³/s, as measured by the Water Resources Bureau of Danba County (Ning et al. 2022). Debris flows originating from the Meilong gully contain sufficient potential energy to impact nearby communities, and an outbreak flood could impact communities along the XJCR (Yan et al. 2021). Although only two deaths were associated with this event, approximately 21200 people were evacuated from their homes as part of the emergency response in anticipation of the
failure of the dam resulting from the debris flow (Zhang et al. 2021). The impacts of the disaster chain are summarized in Table 1.

| Measurement                  | Types of impacts                                                                 |
|-------------------------------|----------------------------------------------------------------------------------|
| Tangible (economic)           | Damage to the highway (5200 m), four bridges, and two hydropower stations.       |
|                               | Damaged buildings: more than 100.                                                |
|                               | Submerged buildings: more than 200.                                               |
|                               | Others: vehicles, damage to factory communication facilities, the costs of debris cleanup and disposal, disaster aid, and postdisaster reconstruction. |
| Intangible (social)           | Death and injury: two deaths.                                                      |
|                               | Others: psychological impacts, outbreak of infectious diseases.                    |
| Intangible (environmental)    | Loss of animal life and land resources (28.6 hm²), damage to habitats, migration of biological communities. |

2.2. Geology and geomorphology

The Meilong gully is located in the eastern region of the Qinghai–Tibet Plateau in the transition zone from the Qinghai–Tibet Plateau to the Sichuan Basin. This area is very well known for its highly active geological structures and multiple and frequent geological disasters (Dong et al. 2018a, 2018b). The location of the disaster chain investigated in this study was close to the convergence of the two fault zones of the Longmen Mountains and the Xianshui River. These two fault zones are very active, and many earthquakes have occurred near them (Xu et al. 2009; Yan et al. 2018; Ji et al. 2020). Topographically, the Xiaojinchuan valley is a deeply incised gorge, and short intense rainfall events occur in this area.

The study area features a Northern Hemisphere subtropical climate. Due to the influence of the topography consisting of high mountains and valleys, a vertical climate gradient has replaced the latitudinal climate gradient, thus forming a regional climate distinct from that of the plateau and basin, namely, the Qinghai–Tibet Plateau monsoon climate. The topography of the study area is obviously controlled by the river, and the topography on both sides is relatively steep, with a gradient ranging from 28° to 62°. The slopes on both sides of the XJCR are not proportional, and asymmetrical gentle terraces occur on both sides of the river. At the gully outlet, the study area is relatively broad and is mostly fan-shaped or long and narrow. The gully in the middle reaches of the XJCR is relatively wide and exhibits a gentle slope. The exposed strata in this area mainly include Sinian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, and Quaternary strata (Yan et al. 2021; Zhao et al. 2021). The total stratal thickness reaches 16000 m. The strata that crop out in the accumulation area of the disaster chain include metamorphic arkose sandstones,
sericite–quartz phyllite layers, and Holocene (Q4ys) barrier lake deposits (gray–black sandy loam, loam, brown–yellow sandy loam, and pebble beds).

2.3. Methods

Both a hand-held GPS instrument (GARMIN GPSMAP, Taiwan, China) and a laser rangefinder (Contour XLRic, Contour Company, USA) were employed to determine the location and damage scope of buildings related to the disaster chain. The laser rangefinder had a maximum range of 1850 m and a maximum measurement accuracy of 0.10 m, and the same rangefinders have been adopted in geological hazard surveys after the Wenchuan and Jiuzhaigou earthquakes and onsite investigations of large-scale debris flow disasters (Chen et al. 2015, 2018). A camera was utilized to photograph the damage state. Both unmanned aerial vehicles (UAVs) and pre- and postdisaster remote sensing images are important ways to quickly determine disaster conditions. These methods have been adopted to determine the distribution of landslides and collapses after earthquakes and have been widely applied in rescue work during debris flows and flash floods (Chen et al. 2017; Tziavou et al. 2018). A UAV (Inspire 2, DJI-Innovations, China) was utilized to acquire photographs along the Meilong gully and the XJCR, which has a length of 6 km. A total of 1010 UAV photos were captured, the maximum flight height was 500 m, and the acquired images were then used to construct a topographic and geomorphic map for further analysis, resulting in a post-disaster image (with a resolution of 0.1 m). The predisaster image used the Gaofen-2 satellite images (China) obtained in April 2018, with a maximum spatial resolution of 0.81 m. Both images were used to determine the relative building location and size and the cultivated area, and the siltation state of the XJCR was also determined by comparing pre- and postdisaster images.

3. Results and analysis

This section presents the overall research results obtained by the above research methods. Because of the overlap between the methods used for each part of the
results, we do not elaborate on which tools (methods) are relevant to each finding. The specific analysis is as follows.

### 3.1. Debris flow disaster chain-induced losses

The high velocity debris flow impacted buildings at the outlet of the Meilong gully and rushed into the XJCR thereafter; the river was blocked and formed a lake. The rising flood submerged the Guanzhou hydraulic dam, which is located 700 m upstream from the Meilong gully. The damage produced by the debris flow is shown in Figure 2. The outbreak flood threatened the lives and property of tens of thousands of people in 17 villages downstream. We focus on the villages located along the highway and XJCR within a range of 12 km. Figure 3 shows the location and the relative elevations of the villages, where $H$ is the relative elevation difference from the river surface to the provincial highway surface (RED); $L$ is the distance to point 0 along the provincial highway, with point 0 corresponding to the location of the Guanzhou hydraulic dam; $l$ is the vertical distance from the provincial highway to the river bank (DHR); and AVG stands for the average.

All buildings and land were swept away in villages No. 1 and No. 2, and the highway was also damaged and washed away. In village No. 1, the average distance from the buildings to the river is 88 m, and the mean altitude difference from the building foundations to the river surface is 9.7 m. The elevation difference between the first building upstream of the village and the water level is 7 m. The cross-sectional area remained unchanged in the reach over a distance of 295 m along the river, which indicates that the flood attained a high flow velocity in this reach. The longitudinal

![Figure 4. State of the villages and highway pre- and post-flood.](image-url)
slope gradually decreased from 8.6% to 3.4% along this reach. This decrease caused the flood to suddenly discharge into the village because the flood flowed from a steep slope to a gentle slope, causing the water level to rise. In village No. 2, the elevation difference between the building foundations and the bridge top surface is only 0.4 m. The bridge became blocked by trees, wooden building parts, and other debris, which caused water to accumulate and discharge into the village from the right bank, finally resulting in buildings being completely damaged and washing away and land entirely disappearing. Villages No. 3 and No. 4 are located in a wide reach section, with a wider flood cross-sectional area, as shown in Figure 4. Hence, the number of damaged buildings was less than that in villages No. 1 and No. 2. Although the flood passed between buildings on both sides, only the outer buildings were damaged. Downstream from this region, the flood imposed little effect on the longitudinal and perpendicular profiles of the river course, and the buildings along the bank were much safer than those in the upstream region.

3.2. Characteristics of the damage to buildings

The building failure types are closely related to the outbreak flood process, which is manifested as a rapid increase in the discharge during the initial stage of the outburst. In the process of a rapid increase in the discharge, the river course mainly experiences strong channel cutting and bank scouring, which can cause houses near the banks to collapse, as shown in Figure 5. During the recession of floods, large amounts of sediments are deposited and accumulate, the channel elevation is raised, and any remaining or damaged houses that are not carried away are buried, as shown in Figure 5. The main factors responsible for flooding-related building damage include the high intensity and destructive power of floods, the low strength of construction materials, unreasonable traditional construction methods, poor structural integrity, and incomplete flood risk management systems. In addition, outbreak floods with a high velocity, large discharge, and carrying more sediment are also causes of building destruction in mountain villages.

Influenced by the local economic level and buildings with cultural characteristics, the buildings are primarily three types according to the structure: stone-masonry structures, brick-concrete building structures, and frame-brick mixed structures, as shown in Figure 6. Building stability is commonly influenced by the following factors:
the impact force of driftwood and stones, the hydrodynamic force of floods, and flood induced foundation erosion. The different types of building structures exhibit their own damage characteristics, which are specifically described as follows: because stone-masonry structures have the lowest resistance to transverse impact, the collapse of a load-bearing wall easily results in the partial or complete collapse of these buildings, and buildings of this structural type are readily damaged and transported downstream along the river by the flood, as shown in Figure 6(a). The brick-frame structure exhibits a high stability. Under the action of intense erosion, cutting and scouring by the flood, the building foundation easily becomes suspended, thus notably reducing the building stability, and eventually, the whole building topples, as shown in Figure 6(b). Brick-concrete building structures experience easy partial failure under the action of driftwood or large stones carried by floods, as shown in Figure 6(c). However, under the strong scouring of the foundation, the whole building may collapse, as shown in Figure 6(d).

Under the strong scouring action and violent impact of the flood or the objects carried by the flood (such as large stones and driftwood), the failure sites of the buildings include the foundation and frontal wall. Due to the sustained impact force, the stability of the building structure decreases, thus leading to overall failure. When the flood velocity decreases, sedimentation may occur indoors. Flood-damaged buildings must be evaluated for the degree of damage, and cleanup and repair are necessary to restore the buildings to useable conditions. When a building survives a flood,
its structural strength, foundation, sill, roof, and walls must be assessed. Compared to repairing a structure with extensive damage, tearing it down and building a new structure is probably less expensive. Buildings with a brick-concrete structure can be partially damaged under the impact of driftwood or large stones, but the structure can be used again after the damaged components are repaired or replaced. Sedimentation causes a building to lose its function, but these buildings can be reused after cleanup; in this case, the flood does not negate the building’s useable function and affects only the building appearance.

### 3.3. Deposit morphology

The study area along the XJCR was predominantly V-shaped, with steeply sloped sides prior to the disaster. This initial morphology was reconstructed, and following the 2020 event, the V-shaped valley floor changed into a wide–shallow shape as sediment was transported and deposited along the river channel. The initial influence of the outbreak flood was a massive increase in the supply of loose material within and along the XJCR channel. The flood carried debris flow-mobilized material downstream, which was immediately deposited in the initiation zone of the debris flow dam, thereby filling the valley bottom, burying both banks, and stripping vegetation from the banks, as shown in Figure 7. The river length affected by sediment scouring and deposition was 6270 m, and villagers indicated that the gully bed was uplifted approximately 15–20 m in Hongwuyue village, Yuezha township, Danba County (at 101.99°E and 30.95°N).

Due to the raised riverbed, the flood eroded the left and right banks, and the river cross-section widened. Figure 8 also shows the cross-sectional change at 102.01°E and 30.96°N, where a bridge was completely destroyed. Before the flood, the width of the river bottom surface was 32 m, the width of the bridge top surface was 51 m, and the clearance height of the bridge was 2.7 m. The slope of this reach was 22°. After the flood, the cross-section at the bridge exhibited a major change. Compared to the original width of the river channel, the left bank increased by 12.2 m, and the right...
bank increased by 57.3 m. The total width of the bottom surface of the river channel reached 101.5 m, which was 3.2 times that predisaster.

### 3.4. Analysis of the blockage effect

#### 3.4.1. Influence of the building layout

The building blockage effect was the most obvious in village No. 4, and this village was selected as an example to analyze the building blockage effect. The buildings were located along the highway and gradually changed from sparse to dense from upstream to downstream, and relatively few buildings were present close to the mountainside. The buildings were divided into four areas, and the highway traversed through the village along the outside, as shown in Figure 8. The frontal building in area I deflected the flood and changed the impact forces. The flood was divided into two parts: some of the water flowed along the original channel, while the remainder

Figure 8. Building blockage effects in village No. 4.
destroyed houses and developed a new channel. The average width of the new river channel was 30 m. The buildings in areas I and II were destroyed under the impact force and deep scouring produced by the flood, and twenty-four buildings in areas I and II were destroyed, as shown in Figure 8(c). After the buildings in areas I and II were destroyed, the flood velocity was reduced due to the large cross-sectional area, which protected the houses in the middle region (area III) from flood impact. These buildings suffered only from the flood inundation effect, and the building structure in area III remained intact. The buildings in area III were newly constructed buildings with a high resistance to the impact force, which further reduced the flood energy. The buildings in area IV were protected, and only the buildings along the edge of area IV were scoured and damaged by the flood. Area IV featured buildings consisting of stone-masonry structures with a poor capacity to resist the impact force, but these buildings were not subjected to direct flood impacts because the surrounding buildings provided a certain blockage effect. Therefore, these buildings with stone-masonry structures were not damaged and were affected only by the sediment burial effect in the late flood stage.

The frontal building was directly impacted by the hydrodynamic force and flood carrier, and they revealed an independent anti-impact effect. The total width of the frontal building accounted for approximately 14% of the width of the river, and it was difficult for these buildings to exert a blockage effect to reduce the overall flood exposure. Thus, these buildings in area I were all badly damaged and collapsed. The buildings in area III not only withstood the flood impact force but also provided effective protection to the rear buildings in area IV. Therefore, the stability of single buildings and the building blockage effect are influenced by the crisscross or parallel building layout on the plane, building density along the downstream direction, vertical water flow, building construction materials, and other factors.

3.4.2. Protection from riparian vegetation zones and highway subgrades

Forested riparian buffers along rivers can dissipate flood energy, reduce flood velocity, change flow direction, and enhance bank stability. Vegetation zones along a river can reduce the risk of flood erosion and alter the energy of floods horizontally and vertically, as shown in Figure 9. Revetment engineering increases the safety of vegetation zones, and the collocation of plants enhances the landscape effect of vegetation zones. Riparian vegetation zones can disperse the water flow and regulate the kinetic energy
of floods, thus reducing the direct impact force of floods on buildings. They may also intercept driftwood and stones carried by floods, reduce discharge through trees and prevent direct impacts to buildings. Figure 8(d) shows that a large number of trees were distributed in area VI, and the trees’ blockage effect was very prominent in the flood disaster. Six buildings were distributed in the area before the disaster, while after the disaster, two buildings within the protection range of the vegetation zone were not damaged. However, the buildings that were not protected by the vegetation zone were severely damaged, and the upstream faces of the buildings were badly damaged via both foundation erosion and wall collapse. A highway located between the river and a village can not only alter the flood direction but also mitigate flood scouring and erosion. Once the highway subgrade is damaged, the buildings located in the upstream area are directly impacted by the flood scouring effect and by the impact effect of objects carried by the flood.

4. Discussion and suggestions

Floods are comprehensive geological, meteorological, and hydrological events that exceed the capability of a community to withstand and overcome (Lindell and Prater 2003; Deria et al. 2020). In addition, postdisaster recovery is an extremely time-consuming process and often takes decades. The investigation and analysis of flood disasters can help policymakers understand flood impacts on residential buildings and populations and then design appropriate protection measures, which help reduce casualties and damage.

4.1. Discussion on the flood control standards in mountain villages

Infrastructure is designed and built to protect against flood events up to a chosen magnitude, and the flood design is defined as a flow quantile with a selected frequency of occurrence or return period (Xiong et al. 2020). For example, a 100-year return period is typical for designing levees and other protection structures (Olsen 2006), and a 20-year return period is selected for designing debris flow mitigation measures to protect highways and world heritage sites (Chen et al. 2015; Zhao et al. 2020). Flood control standards correspond to the protected object; thus, the design standards should fully consider economic, social, and environmental factors. The levels of economic and social development in rural mountainous areas are relatively low, and many houses are self-built and are commonly unprotected, thus resulting in serious loss of life and property during floods (Li et al. 2011).

According to several relevant flood control standards issued in China, there are no unified standards in large rural areas (Xie et al. 2012; Mei et al. 2014; Yu et al. 2018). The flood control standards of rural communities are related to the population size and cultivated area. The control standards are a 10~20-year return period for a population size smaller than $20 \times 10^4$ and a cultivated area smaller than 200 km$^2$. The standards of small- and medium-sized enterprises are a 10~20-year return period and a 20~50-year return period, respectively. Other countries also have different flood control standards for rural areas (Cheng 1998). For example, a 50-year return
period was selected in the United States and Japan, a 20-year return period was selected in India, and a 25-year return period was selected in Russia. According to flood severity, geographic conditions, and social and economic development conditions, flood control standards should be formulated for various protection objectives.

Moreover, the population size and cultivated area of the villages in mountainous canyon areas are far less than that limit. There are also no corresponding reference standards for villagers when constructing buildings. Therefore, it is urgent to determine the building number and population size in the villages along mountain rivers and then draw a relation curve of the flood level, peak discharge, and submerged building quantity, which could help disaster managers make decisions corresponding to different flood frequencies, as shown in Figure 10.

4.2. Suggestions

Based on the above analysis, the following suggestions are formulated in terms of village planning, highway construction standards, and housing design standards in mountainous areas:

1. We recommend that flood levees, highway subgrades, bridges, and village planning adopt the standard of a 50-year return period. In other areas, the standards of highway subgrades could be lower than that. After every three to five bridges with low design standards, a bridge should be built with a 50-year return period, which can guarantee normal traffic conditions between the villages on the left and right banks if some of the bridges are damaged.

2. The flood control standard of a 50-year return period should be considered in the planning and site selection of new village buildings, and a reasonable distance should be maintained between buildings and the river. By increasing the elevation difference between the building foundation and the flood surface, if the elevation of the existing building foundation is lower than that of the designed flood level, the building structure should be moved or partially reinforced.

3. Based on the main damage types of the buildings, the layout should fully utilize the blockage effect of surrounding buildings to reduce the overall construction

![Figure 10. Sketch map of the relation among the water level, flood discharge and submerged buildings.](image-url)
cost. The design standard of buildings near the river and in the upper reaches should be raised, structures with a high impact resistance capacity should be adopted, and the anti-erosion ability of building foundations close to rivers should be enhanced. The standard of the anti-erosion ability of the building foundation could be gradually reduced, with increasing distance between the building and the river to reduce the construction cost.

4. A combination of engineering and vegetation measures should be implemented, and the vegetation zones could fix soil and prevent erosion, as shown in Figure 11. Engineering protection measures should be established along the building direction facing the river, and forests should be planted in advance. Protection engineering could reduce the degree of damage to buildings during floods. Moreover, the resilient design method of buildings, various flood risk management methods, and property insurance policies should gradually be promoted and applied from urban cities to rural mountainous villages.

5. Conclusions

This article discusses the types of building damage and flood control standards in rural mountainous areas to attract more scholars’ attention to disaster prevention and mitigation in remote areas. To analyze the threats and hazards that floods represent to village buildings in mountainous canyon areas, we take the disaster chain that occurred in Danba County, China, as an example. The following conclusions are drawn.

1. This study identified the building damage type. The main building structures included three structural types with different failure characteristics. However, the undamaged buildings were flooded or silted by sediments, which affected only their appearance, while their function remained.
2. The building layout influenced the blockage effect. Upstream buildings were directly exposed to flood impacts and provided protection to rear buildings, and the surrounding buildings protected the buildings in the middle.
3. Changes in river topography. The cross-sectional shape of the channel bed along the studied reach changed from a V shape to a wide–shallow shape. The river length that was significantly affected by sediment scouring and deposition was 6270 m, and the gully bed was notably raised by approximately 15–20 m.
4. This study recommends a flood control standard for reference. The flood control standard of a 50-year return period should be applied in villages, and the design standard of bridges at certain intervals should adopt a 50-year return period. In other areas, the standard could be lower than that in village areas.

Disclosure statement

The authors have no conflicts of interest to declare.

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Data availability statement (DAS)

The authors agree to make data supporting the results or analyses presented in this article available upon reasonable request from the first author and corresponding author.

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