Landslides Triggered by the 1970 Tonghai $M_s$ 7.7 Earthquake and their Distribution Characteristics

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Abstract. On January 5, 1970, a $M_s$ 7.7 earthquake occurred in Qujiang River valley, Tonghai County, Yunnan Province, China, with many induced landslides. In this study, the black-and-white KeyHole satellite images were downloaded before the earthquake on February 12 1969, and after the earthquake on March 17, 1970. Then based on the downloaded images, the visual interpretation of landslides in the earthquake intensity district with 8–10 degrees was carried out on the ArcGIS software platform. As a result, a landslide inventory composed of 640 landslides is established. The landslides are mainly distributed on both sides of the Qujiang River valley that developed along the seismogenic fault, Qujiang fault; the interpreted landslides are all large, with an area of 150–74387 m$^2$. In addition, there are 384 landslides with an area of 1000–10000 m$^2$, accounting for 60% of the total number of landslides. Affected
by the quality of the images, the interpreted earthquake landslides are larger than those of the other earthquakes, such as the 2014 Ms 6.2 Ludian earthquake and the 2015 Ms 7.8 Nepal earthquake. The seismic landslide inventory obtained in this study can provide basic data for the follow-up research. The findings have substantial implications for earthquake and seismic landslide disaster prevention and mitigation in high-earthquake intensity locations.

**Keywords:** The 1970 Ms 7.7 Tonghai earthquake; Seismic landslide inventory; Keyhole satellite image; Landslide distribution

### 1. Introduction

Seismic landslide is an essential secondary earthquake disaster, which often cause significant economic losses and heavy casualties\(^1\). For example, the seismic landslides triggered by the 1920 Haiyuan earthquake caused about 100000 deaths\(^2\), the seismic landslides triggered by the 2008 Wenchuan earthquake caused about 20000–30000 deaths\(^3\), and the seismic landslides triggered by the Peru earthquake on May 31, 1970, caused about 23000 deaths\(^4\). Therefore, the study of the distribution of seismic landslides, especially those of the strong earthquakes, is great significance to the prevention and mitigation of seismic landslides. Therefore, a complete inventory of seismic landslides is the premise of the study of the seismic landslides distribution. With the development of remote sensing and computer technology, more and more seismic landslide inventory have been established in recent years. For example, the 1999 Mw 7.6 Chi-Chi earthquake, Taiwan\(^5\); the 2002 Mw 7.9 Denali earthquake, America\(^6\); the 2005 Mw 7.6 Kashmir earthquake, Pakistan\(^7\). The 2008 Mw 7.9 Wenchuan earthquake, China\(^8\); the 2010 Mw 7.0 Port-au-Prince earthquake, Haiti\(^9\); the 2015 Mw 7.8 Gorkha earthquake, Nepal\(^10\). On this basis, experts and scholars have carried out many research works on the distribution characteristics, development mechanism, and landslide susceptibility evaluation of seismic landslides and achieved fruitful results.

On January 5, 1970, and Ms 7.7 earthquake occurred in Tonghai County, Yunnan Province, China. The earthquake’s epicenter was located in the Qujiang River valley at the junction of Tonghai, Eshan and Jianshui counties in Yunnan Province. The epicenter coordinates is 24.1°N, 102.6°E (https://www.cenc.ac.cn/). The focal depth is 13 km, and the affected area is about 8800km\(^2\). The earthquake killed 15621 people, disabled 26783 people, and collapsed 338000 houses\(^11\)\(^12\). After the earthquake, many scholars have studied the characteristics of the earthquake sequence, the earthquake...
source, the coseismic deformation, and the break sliding of the earthquake\cite{11}\cite{13}\cite{14}. These studies mainly focus on studying the earthquake mechanism, but the study on seismic landslides is a little lack. To provide a useful supplement for the global coseismic landslide inventories and provide basic data for evaluating seismic landslide susceptibility in this earthquake-prone area. In this paper, based on the KeyHole satellite images, the landslides were visual interpretation on the ArcGIS software platform, and the coseismic landslide inventory was established. The distribution characteristics and scale of the landslides were preliminarily analyzed.

2. Geological structure of the study area

The Tonghai earthquake struck the Qujiang River valley, which is situated in the convergence zone of the North-South seismic region. The Jinhe-Lijiang fault, the Anning river fault, the Xiaojiang fault, the Chuxiong-Jianshui fault, and the Honghe fault\cite{15} are all part of the Sichuan-Yunnan rhombic block’s subsidiary blocks in central Yunnan (Figure 1). Because the Sichuan-Yunnan rhombic block moved to the SSE direction, and the Tonghai earthquake area hindered the movement of the rhombic block, the stress concentration in this area was caused, and the moderately strong earthquake concentrated area was formed\cite{13}. The seismogenic structure of this earthquake is the Qujiang fault, the length is about 80 km, a deep fault cutting through the strata of the Sinian, the Cambrian, the Devonian, the Carboniferous, the Permian, the Triassic, the Jurassic, the Quaternary and the Neogene\cite{16}\cite{17}. The fault plane inclines to the NE direction and owns characteristics of right-handed strike-slip thrusting since the Quaternary\cite{17}.
**Figure 1.** Tectonic background map of the study area. GZ-YSF: the Ganzi-Yushu fault; XSHF: the Xianshuihe fault; LMSF: the Longmenshan fault; ANHF: the Anning River fault; CX-JSF: the Chuxiong-Jianshui fault; HHF: the Honghe fault; JSJF: the Jinshajiang fault; JH-LJF: the Jinhe-Lijiang fault; ZMHF: the Zemuhe fault; QJF: the Qujiang fault; XJF: the Xiaojiang Fault; ∈: the Cambrian; C: the Carboniferous; D: the Devonian; J: the Jurassic; N: the Neogene; None: The lithology of the formation is unknown; P: the Permian; Q: the Quaternary; T: the Triassic; Z: the Sinian; E: the Paleogene.
3. Data and methods

The images used for landslide interpretation are the black-and-white KeyHole satellite images before the earthquake on February 12, 1969, and after March 17, 1970, as shown in Figure 2. Because the KeyHole satellite image data source lacks geographic coordinates and projection system information, there is some overlap among the downloaded images. As a result, before the landslide interpretation, the image must be cropped and geo-referenced numerous times. Firstly, on the platform of ArcGIS software, the border of the image and the overlapping area of adjacent strips are cut for the first time. Then, the ground control points with obvious characteristics such as road inflection, river, and typical landform points are selected in the Google Earth image with geographic coordinates. On the platform of ArcGIS software, the third-order polynomial transform is used for accurate registration. This step was repeated, and many times of geo-registration was down. Finally, the images before and after the earthquake, including geographic coordinates and projection system, were obtained. After verification, the position error of the images before and after the earthquake is less than 10 m, which meets the requirements of visual interpretation of landslides. Based on the images after the geo-registration, by comparing the image brightness changes before and after the earthquake in each region, the seismic landslides are delineated with the surface elements on the ArcGIS software platform.

Figure 2. Satellite image of the study area.

4. Results and analysis
4.1. Landslide number and landslide area

A total of 640 landslides were interpreted by visual interpretation. The total area of landslides is 3.01 km², and the area of single landslides ranged between 150–74387 m². Typical landslide cases are shown in Figure 3. The single landslide areas are divided into 4 levels: <100 m², 100–1000 m², 1000–10000 m² and >10000 m². The landslide number in each level is counted and analyzed. There are 182 landslides with an area of 100–1000 m², accounting for 28.44%, 384 landslides with an area of 1000–10000 m², accounting for 60%, 74 landslides with an area >10000 m², accounting for 11.56% of the total number of landslides.

![Figure 3. Typical interpreted landslides. a and d are images of before earthquake, b and e are images of after earthquake, c and f are current Google Earth images.](image-url)
4.2. Analysis of landslide density

The density map of landslide points is created on the ArcGIS software platform based on the landslide inventory obtained through interpretation, as illustrated in Figure 4. Because of the large scope of the study area and the wide range of the landslide distribution, 1500 km was selected as the search radius to make the landslide point density map. As a result, the high-density areas of landslides are mainly distributed on both sides of the Qujiang River valley, and the largest landslide point density is 7.36/km².

![Map showing landslide density](image)

**Figure 4.** The map shows the landslide points density.

5. Discussion

The seismic landslides generated by this earthquake are compared to those triggered by the Ms 6.2 earthquake in Ludian in 2014 and the Ms 7.8 earthquake in Nepal in 2015. The Ludian earthquake has generated a total of 10559 landslides. The landslides with an area of 100–1000 m² is the most, which has 7083, accounting for 67.08% of the total; The landslides with an area >10000 m² is the least, which has 211, accounting for 2% of the total; There are 611 landslides with an area <100 m², accounting for 5.79% of the total; There are 2654 landslides with an area of 1000–10000 m², accounting for 25.13% of the total. The Nepal earthquake triggers 47200 landslides. The landslides with an area of 100–1000 m² are the most, with 24109, accounting for 51.08% of the total. The landslides with an area >10000 m² are the least, with 2064, accounting for 4.37% of the total. There are 2668 landslides with an area <100 m², accounting for 5.65%. There were 18359 landslides with an
extent of 1000–10000 m², accounting for 38.90% of all landslides. Through comparison, it can be found that the landslide areas of these two earthquakes are mainly in 100–1000 m², while the landslide areas of Tonghai earthquake are mainly in 1000–10000 m², and the coseismic landslide areas of Tonghai earthquake are relatively large (Figure 5.). The reason is that the image used for the interpretation of Tonghai seismic landslides is black-and-white color and have low resolution, which may leads to the omission of some small landslides.

Figure 5. The landslide area distribution of three earthquakes.

6. Conclusion

Based on the KeyHole satellite images before and after the earthquake, the landslide inventory of the 1970 Tonghai earthquake in Yunnan Province that consists of 640 landslides is established by using the visual interpretation method. The landslide area is mainly in 1000–10000 m², and the landslide high-density area is located on both sides of Qujiang River valley. The research results can provide a reference for the prevention and assessment of seismic landslide disaster in this earthquake-prone area, and add a new coseismic landslide inventory for large earthquakes all over the world.

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