A database of landslides triggered by 2014 Mw 6.1 Jinggu earthquake, China

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Abstract. On October 7, 2014, a Ms 6.6 earthquake occurred in Jinggu County, Yunnan Province, China, causing some casualties and property damage. A database of landslides was created based on high-resolution satellite images taken before and after the earthquake. The results show that this event triggered at least 441 coseismic landslides, with a total area of 1.08 km², distributed in the VII-VIII intensity zone, with an area of about 2160.86 km². The total volume of these landslides is estimated to be $9.4 \times 10^6$ m³ according to the area-volume formula. The point density, area percentage, and volume density of the landslides in the study area are 0.20 km⁻², 0.05%, and 0.004 m⁻¹, respectively. The comprehensive results show that the Jinggu earthquake landslides are mostly relatively small-scale and develop in a wide range. We consider the influence of topographic factors and river systems on coseismic landslide distribution using landslide number density (LND) and land area percentage (LAP). It indicated that LND and LAP generally increase as the elevation and distance to watershed decrease and slope angle increases and are relatively larger in southeast-facing and concave slopes. This detailed coseismic landslide database for the Jinggu earthquake is essential for the subsequent regional risk assessment.

1. Introduction

On October 7, 2014 (Beijing time 21:49), a Ms 6.6 earthquake struck Jinggu County in Yunnan Province, China, with the epicenter located at 23.39 N, 100.46 E, and the focal depth of ~ 5 km [1]. Even though the main earthquake's magnitude was slightly higher and the focal depth was shallower than the Ms 6.5 Ludian earthquake nearly two months ago, the damage was minor. This is related to the building characteristics of the two earthquake areas [2], but the nature of this phenomenon is that the number of coseismic landslides is relatively small. The coseismic landslide occurrence is influenced by many factors, among which topography and geomorphic environment should be essential factor affecting the distribution of coseismic landslides.

After the earthquake, China Seismological Administration organized an on-site emergency team to conduct a preliminary investigation in the earthquake area. The results showed that the Jinggu
earthquake affected an area of about 12,000 km², mainly causing the disaster in Jinggu County, nine neighboring counties or districts, and 37 towns [3]. VIII degree of seismic intensity zone primarily involves four villages and towns, including Yongping, Weiyuan, Yizhi, and Bi'an in Jinggu County, Pu'er city, with an area of 395.63 km². VII zone covers an area of about 1765.23 km². In this paper, we took the VII-VIII degrees of seismic intensity zones as the study area and delineated the coseismic landslides triggered by the 2014 Ms 6.6 Jinggu earthquake based on remote sensing interpretation in detail, and analyzed the topography factors and river system on the influence of the landslide distribution.

2. Study area

Figure 1. Maps showing the tectonic setting of the 2014 Jinggu earthquake. (a) The tectonic setting of Sichuan-Yunnan rhomb blocks in southeast Tibetan plateau. The white box shows the scope of (b). (b) Detailed tectonic setting and seismic intensity zones of the 2014 Jinggu earthquake.

The 2014 Ms 6.6 Jinggu earthquake occurred in the southwestern Yunnan province, the southeast Tibet Plateau, where strong tectonic movements are under the background of collision between the
The area near the Jinggu earthquake is characterized by mountains and plateaus, where valleys and basins developed, but the topographic fluctuation is generally small. Except for some medium mountains, the rest is mainly low mountains. The Lancang River flows into Jinggu County and detours in the west. The general terrain slopes from north to south and gradually extend to the east and west. In this area, it is the subtropical mountain monsoon climate with an average temperature of 22.1°C. The external dynamic action mainly includes fluviation and chemical weathering, and the weathering intensity is generally weak. The lithology is dominated by Mesozoic sandstone and mudstone [2, 7-10].

Jinggu County is located in the Lanping-Simao basin between the Simao-Puer seismic zone and the Gengma-Lancang seismic zone on two sides of the Lancang River fault, namely the southwest section of the Wuliang Mountain of the Hengduan mountain range. Wuliang Mountain is located on the west side of the Honghe fault, the junction of Sichuan-Yunnan rhomboid block, Mizhina-Ximeng block, and SW Yunnan block. The Wuliangshan fault zone starts from the northern foot of Wulian Mountain in the north, passes through Zhenyuan, Pu’er, and Mantang to the southeast, and entered Laos along Yingpan Mountain in the east. It is mainly composed of three secondary faults, namely Mohei fault, Pu'er fault and Puwen fault (Fig.1) [3, 5, 11].

In history, the largest earthquake that occurred along the Wulianshan fault zone was an M6.8 Mohei earthquake in 1979 [12]. Historical earthquakes near this region mainly occurred in Ning’er, Mohei, and Simao areas, while rare in the Jinggu area [12]. Sixteen earthquakes above M5, 12 earthquakes above M6, and 3 above M7 within 100 km from the Jinggu earthquake area were recorded. The largest one is the Lancang-Gengma M7.4 earthquake in 1988 [2, 5]. Until the 2014 Ms 6.6 Jinggu earthquake occurred, there have been 2664 days without earthquake activities in Jinggu County, exceeding the longest interval of 2536 days for an M5 earthquake in history [4].

3. Data and methods

3.1 Data

The post-quake satellite images are compared to pre-quake satellite images to identify coseismic landslides. The pre-quake Gaofen satellite images are obtained by fusing multispectral images and panchromatic images with a resolution of 2 m. The pre-quake images are supplemented by RapidEye-1 and RapidEye-3 images with a resolution of 5 m to cover the study area. The post-quake images are mainly made of fusing Gaofen images (resolution of 0.8 m) and RapidEye-3 images (resolution of 5 m), which cover the study area enough to recognize small landslides to produce a high-quality inventory map.

In this study, five factors, including elevation, slope angle, aspect, curvature, and distance to the watershed. Four topography parameters were retrieved using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER GDEM, http://www.gscloud.cn/sources/accessdata/310?pid=302) digital elevation model (DEM) with a 30-m resolution. By outlining satellite pictures and comparing DEM data, watershed data was generated. 3.2 Methods

In this study, visual interpretation of satellite images is used to compiling a coseismic landslide inventory, based on the availability of this method for earthquakes in mountainous areas [13]. In the process of visual interpretation, we represented a landslide by a polygon and a mass point of the polygon. The point-based inventories describe locations of landslides, and the polygon-based inventories depict scales of landslides.

The elevation was divided into five classes with an interval of 300 m; the slope angle was split into six classes with an interval of 10°. The slope aspect meaning the facing direction of a slope, was divided into nine classes. Among them, the flat area is horizontal with a zero slope angle [14, 15]. Slope curvature, which means the amount that slope is curved, was divided into six classes. Negative curvature indicates a concave slope, and positive curvature indicates a convex slope. A slope, with
zero or near zero curvature is a straight plane. The distance to the watershed also is considered as an influencing factor with a 100 m buffer interval. Furthermore, we discuss the correlations of these factors with the distribution of coseismic landslides and identify the conspicuous factors through statistical analysis based on Intersect function in ArcGIS.

Figure 2. Coverage of satellite images of the Jinggu earthquake affected area. (a) Pre-earthquake images. (b) Post-earthquake image. The green boxes show the Gaofen images; the red, yellow, and blue boxes show the RapidEye-1, RapidEye-3, and RapidEye-5 images, respectively.

4. Results

The results of remote sensing analysis show that the Jinggu earthquake-triggered 441 landslides in an elliptic study area with an area of 2160.86 km2 within a seismic intensity zone greater than or equal to VII degrees. The total occupation area of the coseismic landslides is 1.08 km2 (Fig. 3). Among these landslides, the area of the smallest is 86.47 m2; the largest is 56143.90 m2. There are 25 landslides with an area of more than 10000 m2, about 42% of the landslides with an area greater than 1000 m2, and only two landslides with less than 100 m2. The overall distribution of these landslides is generally along an NW-SE direction long axis and relatively concentrated in the southeast of the epicenter (Fig. 3). The density of landslide points in the whole study area is 0.20 km$^{-2}$; the area percentage is 0.05%.

The volume of seismic landslides can be obtained using the “area-volume” power law formula. An “area-volume” formula of landslides was obtained using the landslides samples in the 2008 Wenchuan Earthquake [16]:

$$V = 1.3147 \times A^{1.2085}$$  \hfill (1)

In the formula, $A$ represents the area of a single landslide, and $V$ represents its volume. To estimate the total volume of landslides triggered by the Jinggu earthquake, this formula was used to calculate the volume of every single landslide triggered by the Jinggu earthquake, respectively. Then the total volume of the landslides triggered by the Jinggu earthquake is obtained, which is $9.4 \times 10^6$ m$^3$, and the landslide volume density is $9.4 \times 10^6$ m$^3$/2160.86 km$^2 = 0.004$ m.
The scale and frequency of earthquake-triggered landslides always have a logarithmic relationship [17, 18], and the results can represent the integrity of the coseismic landslide inventory. On the logarithmic coordinate axis, Fig. 4 depicts the relationship between the cumulative number $N$ of Jinggu earthquake landslides and the area $A$ of individual landslides. By linear fitting, the relationship between the two variates can be expressed as the following formula:

$$\ln N = 0.7926 \ln A + 4.5795$$

Figure 3. Landslides triggered by the 2014 Jinggu earthquake

Figure 4. Correlation between the cumulative landslide number and the landslide area related to the Jinggu earthquake
It is inevitable to omit some medium- or small-scale coseismic landslides in landslide inventory during a single earthquake event. Therefore, in the part of small-scale landslide, the line segment will show an obvious downward bending trend, which also is reflected in many previous earthquake cases [17-20]. Bended sections often indicate that the landslides with the corresponding size have been significantly omitted. For example, it can be seen from Fig. 4 that the area of the landslide triggered by this earthquake began to show an obvious bending value of about 300 m$^2$. This indicates that coseismic landslides with an area greater than this value were hardly left out, while those with an area less than this value may be missing because they are difficult to identify on satellite images.

5. Discussion

We show the correlation of landslides spatial distribution and topographic factors and watershed by LND (defined as the number in each factor class) and LAP (defined as the percentage of the landslide area in each class of each factor).

In the study area, the elevation ranges from 683 to 2292 m and is dominated by 1000–1600 m. The values of LND and LAP both decrease with increasing height (Figs. 5a and 5b). The LND values mostly have a negative linear relationship with elevation (Figs. 5b).

The slope angle range in the study area is 0–70.5º, and the area with an angle of 10–20º is the largest. The LND generally has positive correlations with the slope angles when the angle does not exceed 50º. The LAP also has generally positive correlations with the slope angles when the angle is less than 40º. The reason for this probably is that the steep slopes are less developed in the study area.

With the exception of flat slopes, the area of each class of slope aspect is fairly average. The southeast-facing slopes have the highest LND peak, followed by the south and east-facing slopes. On the east, southeast, and south-facing slopes, the LAP is barely larger than on the other aspects (Figs. 5e and 5f). The LAP of the north- and northeast-facing slopes, on the other hand, is significantly larger (Fig. 5f).

Slope curvature is another topographic factor that influences landslide distribution. The majority of the slopes are straight slopes, as shown in Figures 5g and 5h. The LND and LAP in relatively straight slopes are smaller. The largest LAP and LND are in the range of >2, which shows that concave slopes are prone to landslides.

Figures 6a and 6b show the landslide distribution in the bands parallel to the watershed. The LND generally decreases with the increase of the vertical distance from the landslides to the watershed, although there are some small fluctuations. The rule on LAP is relatively unapparent.

6. Conclusion

Based on the visual interpretation of high-resolution satellite images, a new and detailed coseismic landslide inventory of the Ms6.2 Jinggu earthquake in Yunnan Province on October 7, 2014, was established. The results show that at least 441 coseismic landslides triggered this event, with a total area of 1.08km$^2$, distributed within seismic intensity zones no less seven degrees with an area of about 2160.86km$^2$. Furthermore, the correlation between landslide distribution and influencing factors indicates elevation, slope angle, and distance to watershed have linear correlations with LND, and southeast-facing and concave slopes are more prone to landslide.

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Figure 5. The landslides distribution in classifications of Topographical factors and their correlations shown by LND and LAP. (a) and (b) elevation; (c) and (d) slope angle; (e) and (f) slope aspect; (g)
and (h) slope curvature. CA: Classification area; LND: landslide number density; LAP: landslide area percentage.

Figure 6. Landslide distribution in buffer of vertical distance to watershed (a) and their correlations (b). LAP: landslide area percentage; LND: landslide number density; CA: Classification area.

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