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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).
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Potential danger of dammed lakes induced by the 2017 Ms6.9 Milin earthquake in the Tsangpo gorge

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A Ms6.9 Milin Earthquake on November 18, 2017 triggered a great deal of new slope failures along the Yarlung Tsangpo gorge. By compared the pre- and post-quake remote sensing images, 529 landslides including rock slides, avalanches, rock falls were identified. The total area of the landslides is 32.42 km^2, and the sediment volume caused by the landslides is estimated to be 0.1 km^3. The landslides also yield 7 dammed lakes of which three large-scale dammed lakes are also affected by nearby debris-flow events in future. A methodology integrating remote sensing, GIS, numerical simulation and hydrological calculation is developed to predict the potential danger of the dammed lakes once large-scale debris flows increase the height of the dams. Preliminary analysis indicates that the storage capacity of the dammed lakes will increase in two cases of debris-flow magnitudes, but the outburst floods may not result in big impact on downstream human settlements.

dammed lake, Milin earthquake, potential danger, risk assessment, Tsangpo gorge, debris flow

Потенциальная опасность подпрудных озёр, образовавшихся в ущелье Цангпо вследствие Милиньского землетрясения магнитудой 6.9

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Милиньское землетрясение магнитудой 6.9 18 ноября 2017 года вызвало много новых обвалов и оползней на бортах ущелья реки Ярлун Цангпо. По итогам сравнения изображений дистанционного зондирования до и после землетрясения были идентифицированы 529 событий, включая горные обвалы, лавины, камнепады. Общая площадь обвалов и оползней составляет 32,42 км^2, а объем их отложений оценивается в 0,1 км^3. В результате обвалов также образовались 7 подпрудных озёр, три из которых имеют значительный объём воды и способны вызвать разрушительные наводнения в будущем. Разработанная методология исследований включает дистанционное зондирование, ГИС, численное моделирование и гидрологический расчет для прогнозирования потенциальной опасности прорыва озёр. Предварительный анализ показал, что объем воды в подпрудных озерах увеличится в двух случаях объемов селей, но прорывные паводки вряд ли приведут к значительным воздействиям на нижележащие населенные пункты.

подпрудное озеро, Милиньское землетрясение, потенциальная опасность, оценка риска, ущелье Цангпо, сель

Introduction

Strong earthquakes often trigger large-scale landslides and dammed lakes such as the 2008 Wenchuan earthquake, the 2013 Lushan, and the 2014 Ludian earthquakes [*Cui et al. 2011; Huang and Li 2008; Xu et al. 2015; Hu et al. 2017*]. The earthquake's seismogenic fault, intensity, and local geological and topographical settings control the distribution and location of the dammed lakes. Some statistical relationships between the seismic parameters and the landslide properties were proposed [*Keefer 1984; Keefer and Wilson 1989; Keefer 2000; Papadopoulos and Plessa 2000; Hancox et al. 2002*].

A Ms6.9 catastrophic earthquake happened on November 18, 2017 at Milin County, Tibet Autonomous Region in western China. As of Nov. 21, 2017, 1416 aftershocks were recorded. The earthquake has induced hundreds of landslides in the Yarlung Tsangpo river. The quake-induced landslides and dammed lakes are interpreted with pre- and post-quake satellite images in this paper. The basic information of these hazards is obtained by GIS analysis on DEM data. In order to evaluate the potential danger of the dammed lakes in near future, numerical simulation and hydrological analysis are combined to estimate the peak discharge of possible outburst floods.

Study area

The study area located in the great canyon of Yarlung Tsangpo river is of the strongest tectonic stress, the highest uplift and exfoliation rate in the Himalaya orogenic belt. where no human inhabits. The earthquake's epicenter is in the extension line of the northeastern part of the Daduka fault (Fig. 1). The elevation of the area ranges from ca. 1303 m to 7782 m. The highest mountain is the Namche Barwa massif (ca.7782 m), and the second highest Gyala Peri massif (ca. 7294 m) is in the northwestern of the area. The average relative relief is about 5,000 meters around the core section of the canyon, which is well known as the deepest gorge in the world. In the deepest part of the Yarlung Tsangpo Gorge between Namche Barwa and Gyala Peri peak, the relative relief reaches to 5,382 meters. The Tsangpo Gorge is the largest water vapour channel on the edge of Tibetan Plateau. The warm and humid monsoon from Indian Ocean makes it one of the highest rainfall areas in the world. The annual rainfall is as high as 4,000 mm in the southern part of the gorge, and between 1500 mm to 2000 mm in the northern part.

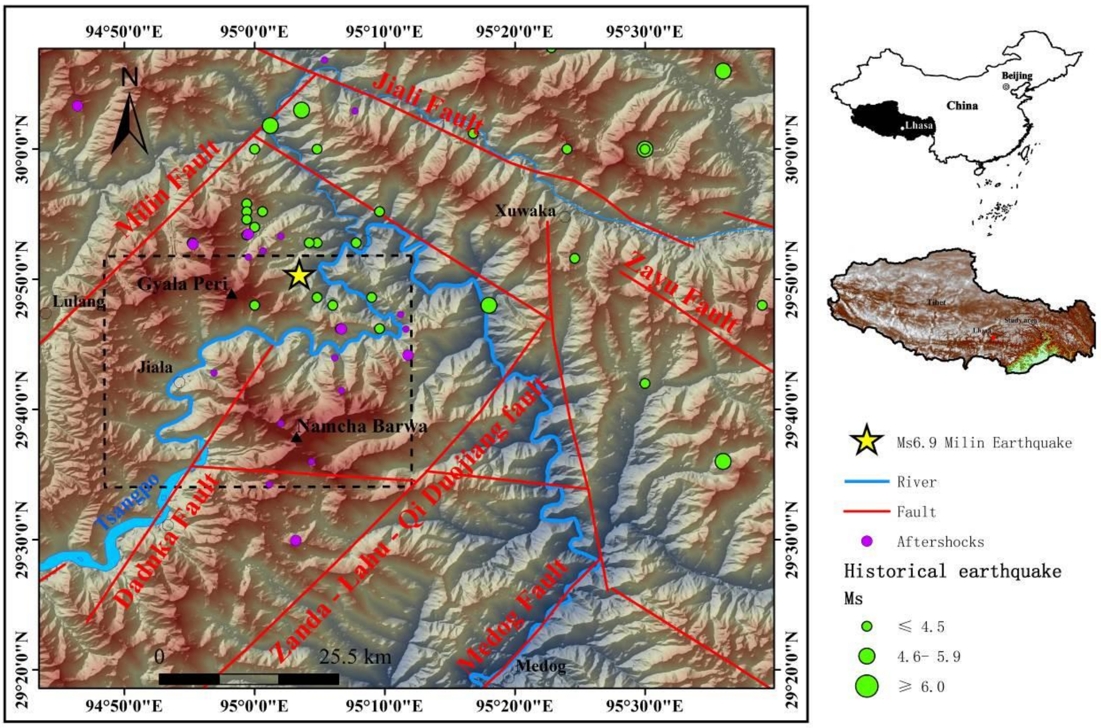

Fig. 1. The location map of the Milin earthquake and historical earthquakes near the Tsangpo gorge since 1950

Dammed lakes after the earthquake

A large number of coseismic landslides were triggered by the earthquake and yielded several dammed lakes in the Tsangpo river. Pre- and post- high-resolution remote sensing images were used to coseismic and post-seismic geo-hazards. The visual interpretation shows that at least 529 landslides including rock slides, avalanches, rock falls etc. distribute along the both sides of the Tsangpo gorge. The distribution of the coseismic geohazards and some coseismic landslides are shown in Fig. 2. In total, the landslides cover approximately an area of 32.42 km^2. Most of these landslides are shallow, and concentrated. The maximum area of the landslides is about 3.62 km^2 and the minimum is 36.95 m^2, while the mean area is about 0.06 km^2. Although there no human inhabits near the epicentre, the dammed lakes may have potential impact on upstream and downstream villages and infrastructures.

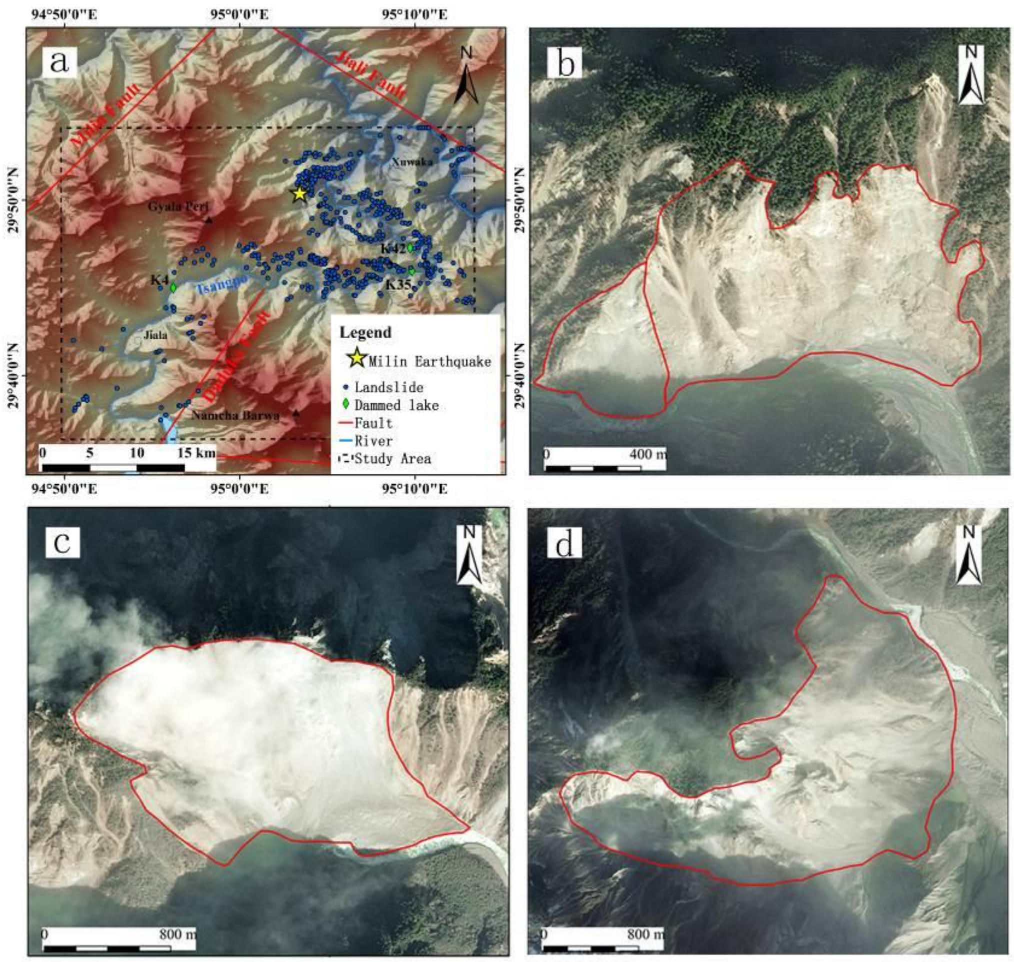

Fig. 2. The distribution of the induced geo-hazards in the study area (a) the blue dot represents the coseismic landslides, and the green diamond represents the dammed lakes, (b), (c), (d) three large-scale landslides interpreted with SPOT 7 image on December 12, 2017.

The earthquake increased greatly the volume of loose materials in the study area. By the area-volume empirical formula proposed by *Larsen et al.* (2010), the total volume of increased sediment is estimated up to 0.1 km^3 (Eq.1). Three large dammed lakes formed after the earthquake, respectively at 4 km (K4), 35 km (K35), and 42 km(K42) downstream of Jiala Village respectively. Combined with Google Earth's pre-quake data and SRTM DEM data and high-precision remote sensing data, the basic information of each of the lakes were obtained (Fig. 3).

$$v = \sum_1^n \alpha A^{\gamma}, \qquad (1)$$

where α is landslide area - volume correction factor (log $\alpha = -0.836 \pm 0.015$), A is landslide area, γ is landslide area-volume experience index ($\gamma = 1.332 \pm 0.005$), n is the number of landslides.

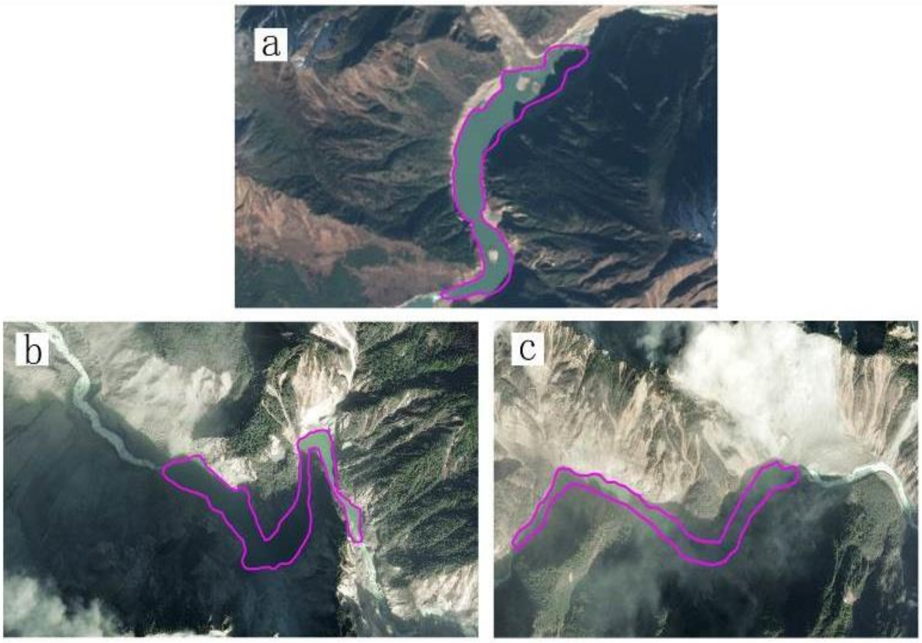

Fig. 3. The remote sensing images of three dammed lakes. (a) K4 from Sentinel with 9.4 m resolution; (b) K42 from Spot 7 with 1.3 m resolution; (c) K35 from Spot with 1.3 m resolution.

Debris-flow hazards

Based on the interpretation of remote sensing images, several debris-flow events occurred at a catchment that is located between the Gyala Peri peak (7294 m) and Namcha Barwa peak (7782 m), and closed to the dam of K4 lake (Fig. 4). The drainage area of the catchment is approximately 66.7 km^2, the main stream is 8.75 km long, and the gradient is around 13.9%. The volume was estimated by the approach proposed by Zhou et al. (1991), the equations are:

$$V_c = 19\frac{T_s Q_c}{72}, \quad (2)$$

where V_c is the total debris volume (m^3); T_s is the total process time of debris flow; Q_c is the maximum discharge (m^3/s).

$$Q_c = \{[0.526(\gamma_s - 1)/(\gamma_s - \gamma_c)](0.58P - 14) + 0.5\}F, \quad (3)$$

where P is sum of rainfall in the first three days before the debris flow(mm); F is total area of the drainage(km^2); γ_c is the debris flow bulk density; γ_S is the soil body bulk density.

According to multi-temporal satellite images from Google Earth, the total volume of the debris flow between 2013 and 2014 was approximately 4.5 million cubic meters. Based on Sentinel remote sensing image on December 10, 2017 and Spot7 remote sensing data on December 12, 2017, another large-scale debris flow event occurred in 2017, with a total of approximately 13 million cubic meters.

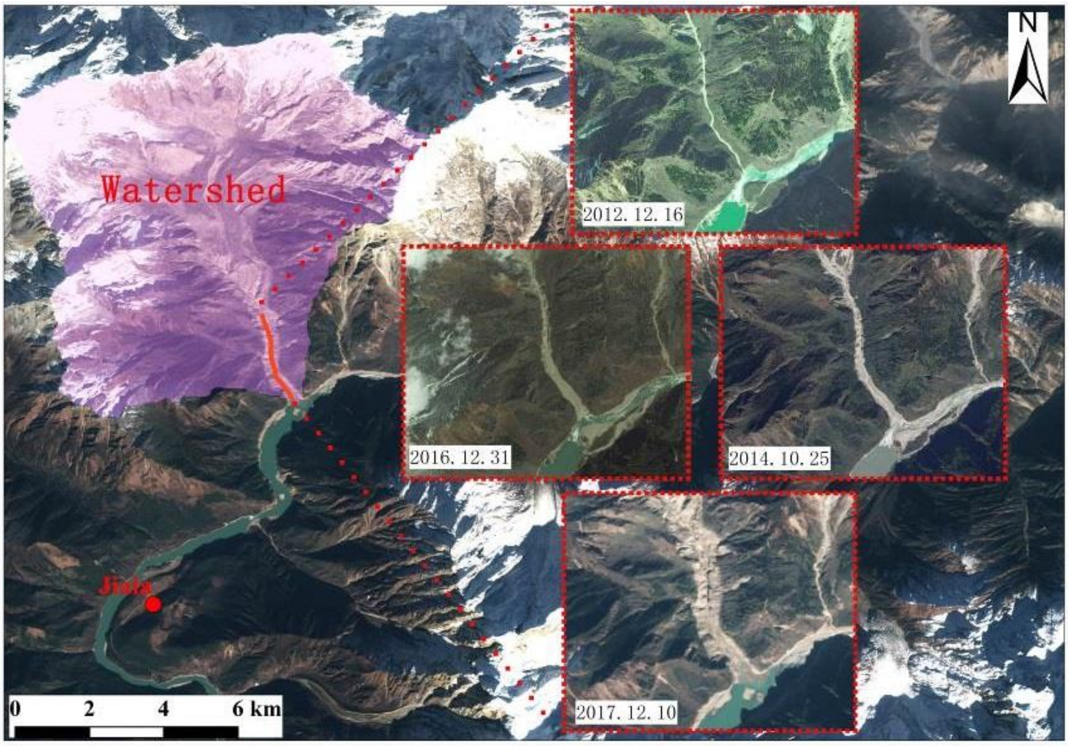

Fig. 4. Comparison of multi-temporal remote sensing images near the K4 lake

Potential danger

The dammed lakes have overtopped and are not dangerous at present. But, the earthquake yields massive loose materials in seven catchments in which debris flows occurred in recent years. Large-scales debris-flow events in near future will dam the Tsangpo river again, and increase greatly the danger of the present dammed lakes. To evaluate the potential danger of the lakes on the condition of large-scale debris flow recurrence, we develop a methodology of assessing the potential danger of the lakes. Firstly, interpretation of multi-temporal remote sensing images is used to analyse the magnitude-frequency relationship of debris flows. Secondly, the dynamic processes of debris flows on different scenarios are numerically simulated on the basis of two-dimensional Saint-Venant equations and suitable resistance model. Thirdly, GIS technique with the high-resolution DEM data is applied to predict the possible capacity of the dammed lakes of which the dams rise by debris-flow deposits. Finally, we use a hydrological empirical formula to calculate the peak discharge of outburst flood once the risen dams broke instantaneously.

With the method above, we considered two cases: a 20-year and earthquake-affected magnitude. Table 1 shows that the simulation results of the changes of lakes' size if different scale debris-flow events happen. Assuming that the dams instantaneously break when the water level reaches the maximum height of the dams, the peak discharge of outburst floods can be estimated as Table 1. The K4 dam lake formed shortly before the earthquake has the largest storage capacity, but the peak discharge (15542 m^3/s) aren't the biggest. However, the K42 lake with a smaller storage capacity has the biggest discharge (29968 m^3/s) (table 1). In these cases, Jiala village may partially be inundated by the K4 lake, and the confluence of Yarlung Tsangpo with Parlung Tsangpo river is affected by backwater at the downstream of the dammed lakes. If a cascade outburst happens for the three lakes, the peak discharge will be much larger than single lake outburst. In the extreme case, some villages at low locations in Medog County could be damaged by the propagating flood wave.

Table 1. The calculated peak discharge of outbrust floods.

Lake no.	**Total capacity (V_w: m^3)**	**Water depth (H_w: m)**	**Average width of the breach (b: m)**	**Peak discharge (Q_{max}: m^3/s)**
K4	5.5×10^7	36	149.5	9917.7
	9×10^7	46	183.4	15542
K35	5×10^7	58	158.8	17419
K42	5.2×10^7	89	174.4	29968

Conclusions

Dammed lakes are typical geological hazards, especially in the area of complex geological structure, high seismicity and highly proned landslide. They often bring catastrophic disasters to settlements and infrastructures at upstream and downstream of them. We use a comprehensive methodology to evaluate the potential danger of the dammed lakes triggered by the 2017 Milin earthquake in the Tsangpo gorge. Interpretation of high-resolution satellite images shows there are 529 earthquake-induced landslides covering an area of 32.42 km^2 in the gorge around the epicentre. The volume of the loose materials increases up to 0.1 km^3 in catchments on the both sides of the gorge. These catchments with such massive loose materials are very susceptible to large-scale debris-flow events if the melting of snow and strong rainfall occur in spring and summer. Moreover, it is found that large-scale debris flows happened and blocked the main river temporarily. Potential danger of three large dammed lakes are analysed under different magnitude of debris-flow events. The risk of the dammed lakes will increase in two different scenarios, but the outburst floods may have a little influence on downstream human settlements.

Acknowledgments

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