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# Distribution Characteristics of Geo-hazards in a Reservoir Area, South Gansu Province, China

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In the process of water storage, due to water level fluctuations and base level erosion, reservoirs also play an important role in the occurrence of geological disasters. Taking a reservoir valley type in South Gansu Province, China as a case study, we investigated in depth the development and distribution of geological hazards and their influencing factors. The geological environment had changed considerably after reservoir impoundment with an increase in geological disasters. Furthermore, the main types of geological disasters were also analyzed systematically. Slope angle, altitude, slope aspect, proximity to earthquake faults, reservoir water storage, slope body structure, rock mass structure, and their combination features influenced the development and distribution of geological disasters in reservoir area. Close proximity to rivers also increases the likelihood of geological disasters. Landslides and collapses are closely related to the geo-hazards and their triggers include earthquakes, torrential rainfall, and fluctuations in reservoir water level. We also identified 2 types of debris which flow into the reservoir: gulch development and slope liquefaction.

[**Keywords:** Characteristics; Distribution; Geological disasters; Influence factor; Reservoir water storage]

## Introduction

In the environment, geological hazards refer mainly to rock and soil instability, due to natural or man-made effects[1-3]. Geo-hazards, including collapses, debris flows, landslides, surface collapses, cracks, and surface subsidence, are more likely to happen as a single disaster or in disaster groups[4]. Geo-hazards are invariably followed by disasters that may threaten people's lives and property[5,6]. Due to landform complexity and strong recent tectonic activity in the upper Yellow River valley region in China, geological hazards frequently occur[7-11]. Tao River is one of the most important tributaries in this region and geologic hazards are distributed widely, especially in the reservoir area, and threaten the safety of large water conservation projects, and also damage the ecological environment, land surface and resources[12-14]. Therefore, understanding the distribution characteristics of geo-hazards in the reservoir area has become an important topic in geological engineering.

In the reservoir area, factors that influence the development of geological hazards have been continuously reported in many papers. However, in the twenty-first century, the compilation of accurate, scientifically-based geo-hazard susceptibility maps at low cost has proven to be difficult. Most research on geo-hazard susceptibility uses different statistics or logic methods with GIS technology[15-20]. In the Three Gorge reservoir area, the entropy model has been employed to quantitatively compute values of different impact factors on geological hazards with Arc GIS. Furthermore, all impact factors are weighted based on the calculation results of the entropy model[5]. A regional three-dimensional (3D) geo-hazard model was established using digital elevation model superposed surface images and geo-hazard elements, based on geo-hazard survey data, using improved boundary representation entity data structure (two-body 3D data structure). The 3D solid model was set up for each hazardous body in each geological hazard map, and used for analyzing the distribution characteristics of geo-hazards in the Three-Gorge reservoir area[21]. Moreover, the reservoir-based landslides are caused mainly by changes in hydrodynamic conditions of the slope interior at the time of water storage or discharge[22]. Through field investigation and the interpretation of remote-sensing information after an earthquake, and using GIS technology, the distribution of earthquake-triggered geo-hazards were analyzed. These earthquake geo-hazards exhibited a zonal distribution along the earthquake fault zone and a linear distribution along the rivers. Topographical slope was identified as the main driver of the development of earthquake geo-hazards[23,24]. Based on topographic elevation, slope angle and seismic intensity, acomparison was made between the number and volume of geo-hazards induced by the Wenchuan Earthquake. Results of this study were then used to analyze the characteristics and formation mechanisms of geo-hazards induced by the Lushan Earthquake, using remote sensing images and field investigation[25]. However, there is a little information on the study of distribution characteristics of geo-hazards in the reservoir area after the reservoir was filled with water.

Due to large scale changes in hydrological/ geological conditions in the process of reservoir impoundment, impacts on the development of geological disasters in the reservoir area are likely, especially as the stability of reservoir bank landslides was evidently affected[26]. For example, pre-existing landslides and debris flows were submerged by reservoir water, leading to significant changes to the reservoir environment, and to the distribution of geological hazards[27]. Additionally, factors that influence the distribution and development of geo-hazards should be further investigated, as this could provide the basis for geological disaster prevention in the reservoir area. Moreover, a better understanding of the distribution characteristics of geo-hazards in a reservoir area after reservoir water storage is needed. Therefore, we selected a reservoir in south China as a case study, for detailed investigation of the distribution characteristics of geo-hazards in a reservoir area after reservoir water impoundment.

## Research methods

### Background and study area

The reservoir is located in the midstream section of the Tao River, which is an important tributary of the Yellow River in China (Fig. 1). It is a typical valley type of reservoir, which includes many ravines and gullies. The terrain is characterized by higher altitude in the west, and lower altitude in the eastern region. The landscape includes mountain and river valley landforms, and the mountain gradient is within 38 - 60°. The mountainous landscape includes three categories: elevation ranging from 2000-3000 m, with a relative difference > 500 m; elevation > 3000 m, with a relative difference >1000 m; and finally, elevation > 3500 m, with a relative difference > 500 m. The gradients are divided into four classes based on terrain slope characteristics:>50°, 40°-50°, 31°-40°, and <30°, respectively. Survey data in the zone shows that geological disasters with a gradient from 30-50° account for more than 50 % of the total[5]. Groundwater in the study area can be divided into two types: loose rock fissure water distributed in the upper and lower reaches of Taoyan, and bedrock fissure water distributed in the upper reaches of Taoyan.

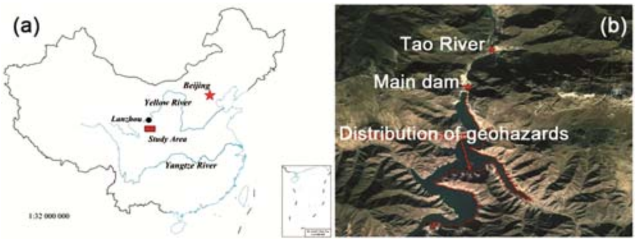

Fig. 1 — Study site location and valley shape features

Pre-Quaternary strata are widely distributed in the study area and include mainly carboniferous (C), Permian (P), Triassic (T), Paleogene, and Neogene (E, N) strata. The lithology of the Carboniferous includes quartz sandstone with shale and sandy slate in reservoir area. The lithology of the Triassic includes quartz sandstone, siltstone, and mudstone. Earthquake activity is frequent in the reservoir area, and seismic intensity of the region is 7 degrees. Concussive uplift is the main recent tectonic movement, and strong mountain uplift, along with sharp water incision have led to the formation of a typical mountain valley. The development of fold and fracture indicates a complex geological structure.

### Research methods

The research is based on detailed field investigation and surveys extending over several years, both before, and after reservoir water storage. During the field investigation process, data on geological disasters in the reservoir area were collected for the analysis of the distribution characteristics of geo-hazards in a reservoir area. The field investigation included collection of data on the distribution and number of debris flows, landslides and collapses. During the field investigation, the previous distribution of geo-hazards in the region were searched from published literature. Additionally, the reservoir area was divided into several survey areas for more detailed survey on the distribution and number of geological disasters.

## Results

### Distribution characteristics of geological disasters

Our field survey and data analysis indicate that geo-hazards distribution in the reservoir area has three characteristics. Firstly, the number of geo-hazards is large, and they are widely distributed. Secondly, geo-hazards have a zonal distribution, especially along the banks of the upstream reservoir area. Thirdly, there are many new occurrences of geo-hazards following reservoir impoundment, many of which are developing.

The distribution characteristics of geo-hazards in the reservoir area can be summarized as follows. Debris flows, landslides, and collapses are numerous and widely distributed in the reservoir area, and there are a large number of new geo-hazards. The main geological disaster types include collapse, landslide, and debris flow, and these three types are dominant, accounting for 94.6 % of total geo-disasters. Only a few loose rock bodies were found.

The number of small geological disasters is approximately twice that of large geological disasters, especially the proportion of small collapse, which is much larger (Fig. 2). So small geological disasters are the main type, and dominate the geological disasters distribution.

Geological disasters are mainly distributed in the upstream area of the reservoir, although there are few near the main dam, which provides the advantage of normal operation (Fig. 3). They are primarily distributed along the reservoir banks and the river valley, whereas the debris flows are generally confined to the river valley. Moreover, according to field survey, landslides were located mainly in the upstream area. For example, in the upstream area of the reservoir, there are 28 landslides, accounting for about 72 % of total landslides. The debris flows were distributed within a certain distance from the river valley in the upstream area of the reservoir, with a linear density within 2-5km.

According to the field investigation, the number of new geological disasters increased after reservoir impoundment, with a large number of new geological disasters developing contemporaneously. Many of these new reservoir bank landslides appeared as a bank slump phenomenon, which was very common (see Fig. 4a). The bank slump phenomenon exhibited high linear density. As a requirement of project construction, a few roads were built in the reservoir area, especially along the reservoir bank. In the process of road construction, a large number of artificial excavation slopes appeared (Fig. 4b), which reduced slope stability, especially under heavy rainfall. Reservoir water impoundment and road construction has provided optimal conditions for the development of new geological disasters, and many should be expected in the future under the influence of external factors.

### Influencing factors

Geological disasters in the reservoir area are influenced by the intensity of earthquakes, landform, strata, and rock type[26], and especially topography, one of the main determinants for the formation of geological disasters[6]. According to the field investigation, the distribution and development of

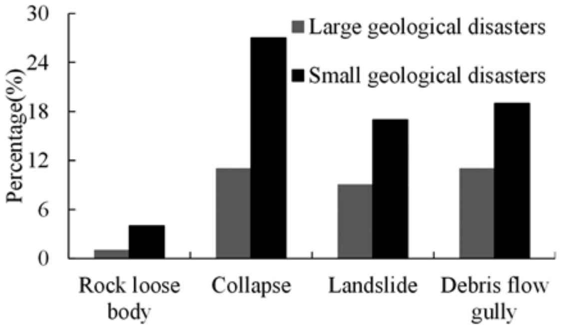

Fig. 2 — Proportion of large and small geo-hazards in the study area.

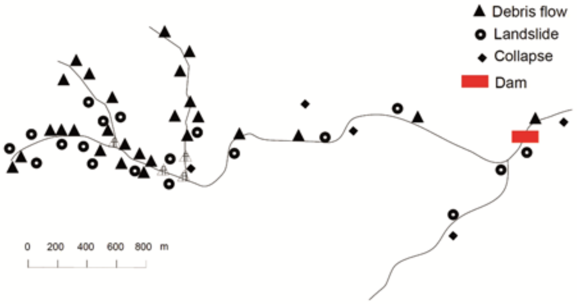

Fig. 3— The spatial distribution of geological disasters

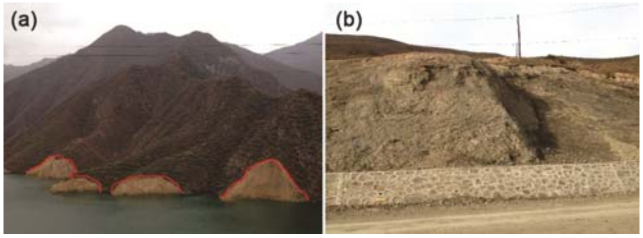

Fig. 4 — Photos of (a) bank collapse and (b) artificial excavation slope

geological disasters are closely correlated with slope angle, slope aspect, altitude, distance from a fault, distance from the river, geo-technical properties, slope structure, as well as reservoir impoundment. The relationship of geological disasters to these factors is explored as follows.

**Slope angle**

Slope angle determines the effective free surface and therefore is a crucial hazard-related factor[27]. In the reservoir area, geological disaster occurrence increased with increasing slope angle[22] and hence slope angle is one of the main controlling factors for the distribution and development of geo-hazards[6].

Most geo-hazards were distributed in the range of 30°-50° in the reservoir area (Table 1, Fig. 5). Furthermore, there were few geo-hazards on <30° and > 50° slope areas. This distribution may be explained as follows. Firstly, for steep slopes from 30° to50°, the rock mass structures are loose, providing ideal conditions for slope failure. Secondly, earthquake activity is frequent in the reservoir area, and it will induce geological disasters under condition of seismic loading[7,8]. To illustrate the influence of slope angle on the distribution of geo-hazards, we analyzed the distribution of landslides as a function of slope, as an example (Table 2). Landslides were mainly distributed on 30°-50° slopes, with, the largest percentage on slopes 31°-40°, and no landslides on slopes > 50°. The development and distribution of geological disasters requires a suitable slope angle, so when the slope angle is < 30° or > 50°, the number of geological disasters are less, and therefore less favorable for the development of geological disasters. Hence, slope angles 30-50° are conducive to the occurrence of geological disasters in reservoir area.

Table 1 — Relation between distribution of geo-hazards and slope angle

| Slope angle (/°) | < 30 | 30~40 | 41~50 | > 50 |
|---|---|---|---|---|
| Landslide | 4 | 18 | 16 | 0 |
| Debris flow gully | 4 | 21 | 18 | 2 |
| Collapse | 3 | 22 | 28 | 4 |
| Rock loose body | 0 | 3 | 3 | 1 |

Table 2 — Area of landslides with different slope class

| Slope class | 0°~30° | 31°~40° | 41°~50° | > 50° |
|---|---|---|---|---|
| Area of landslide ($m^2$) | 8,120,000 | 25,600,000 | 28,730,000 | 0 |
| Percentage of total area of landslides (%) | 12.98 | 41.02 | 46.0 | 0 |

**Slope aspect**

Slopes of different aspect receive differing levels of sunshine, which influences evaporation, vegetation cover, slope erosion, groundwater, and even rock properties[26,27]. Thus, slope aspect influences slope stability, and is therefore a crucial factor in assessing mountain hazards. There was a significant positive correlation between landslide area and slope aspect. For N, NE and NW slope aspects, landslide occurrence is low (6.4, 5.8 and 6.8 %, respectively), indicating that north facing slopes are less susceptible to the development of landslides (Table 3). However, for SE and S aspects, the percentage of landslides was the highest (25.7 and 22.5 %, respectively), which means that these slopes are more prone to land sliding. Therefore, slopes with north-facing aspects are more susceptible to landslides than those with southwest and south-facing aspects in the reservoir area.

**Altitude**

It is generally believed that altitude has no influence on geo-hazard susceptibility, however, it appears to influence the development of geo-hazards in the reservoir area. For example, altitudinal differences in precipitation, plant cover and soil types could be sufficient to create an indirect relationship between altitude and landslides[27]. Geo-hazards at different altitudes can be divided into four zones, and are mainly distributed between 2200 and 3,000 m

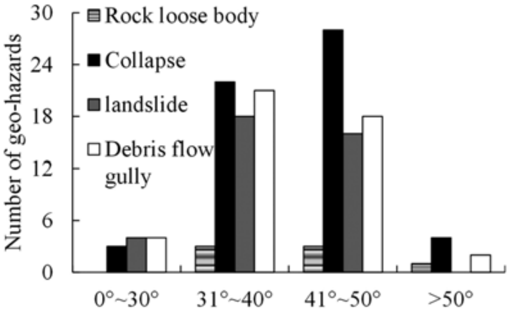

Fig. 5 — Relationship between geo-hazard distribution and slope

Table 3 — Area of landslides with different slope aspect

| Slope aspect | N | NE | E | SE | S | SW | W | NW |
|---|---|---|---|---|---|---|---|---|
| Area of landslides ($\times10^6 m^2$) | 3.99 | 3.62 | 6.43 | 16.05 | 14.06 | 8.68 | 5.37 | 4.24 |
| Percentage of total area of landslide(%) | 6.4 | 5.8 | 10.3 | 25.7 | 22.5 | 13.9 | 8.6 | 6.8 |
| Area of slope aspect zone($\times10^6 m^2$) | 32.4 | 41.3 | 56.8 | 98.7 | 93.2 | 65.2 | 45.9 | 38.4 |
| Percentage of slope aspect zone (%) | 16.5 | 15.9 | 27.5 | 36.3 | 36.1 | 35.3 | 41.7 | 28.7 |

(83.89 % of the total), and in particular between 2,200 and 2,500 m, accounting for 47.0 % of the total (Table 4). However, it accounts for 10.89 % and 11.31 of the total number, < 2200 m and > 3000 m, respectively, which means the lower and higher altitudes are not favorable for the development of geo-hazards. The number and density (2.43/km$^2$) of geo-hazards is greatest from 2200 to 2500 m, which is due to steep terrain slope, stronger rock mass unloading, and the seismic susceptibility which has a greater impact on the development of geo-hazards. Moreover, the density, number, proportion, and area of geo-hazards at this altitude, indicates an optimal condition for their development in the reservoir area.

**Distance from earthquake faults**

There are four faults extending into the reservoir area that govern the occurrence of landslides and avalanches. There are others that could influence hazards, but all are <2200 m long, and not considered significant in this discussion, since it is not feasible to ascertain their distance from the geometric center of land slides. Most landslides are within 3,000 m of the main fault, covering more than 80 % of total landslide area (Fig. 6). Percentage of total landslide area is the greatest within 1000 - 3000 m of the main fault, and declines rapidly at distances > 3,000 m, These patterns highlight that the main fault has a dominant influence on landslide occurrence up to 3000 m.

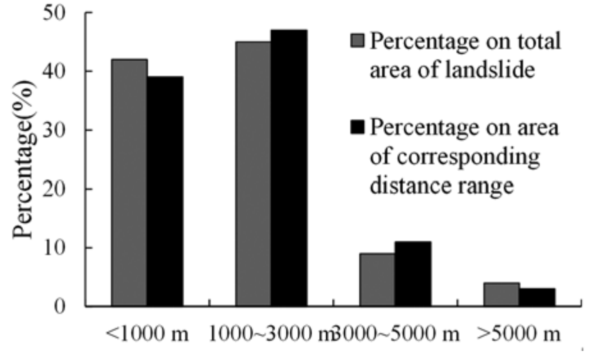

Fig. 6 — Landslide percentage area at different distances from the main fault

**River and valleys**

River erosion has an influence on regional geological structure to a certain degree, and it also has an impact on geo-hazards in the reservoir area. The number of collapses, landslides, and debris flows decreased with increasing distance from the river (Fig. 7a). For example, the number of collapses were 26, 14, and 7, at distances of 0-0.5, 0.5-1.0, and 1.0-1.5 kms from the river, respectively. Furthermore, 50 % of total geological disasters occurred within 0-0.5 km from the river. For example, there were 18 landslides, 15 debris flow gullies, and 26 collapses in at 0-0.5 km from the river. Moreover, the highest number of total geological disasters were also distributed from 0 to 0.5 km of the river (Fig. 7b).

**Reservoir water storage**

There were 124 total geological disasters recorded before reservoir impoundment and 149 after, and the types, and total geological disasters increased (Fig. 8a, b). Moreover, reservoir impoundment increased the number of landslides from 23 to 39. However, it had a trivial impact on loose rock events (Fig. 8a). According to field investigation, many new

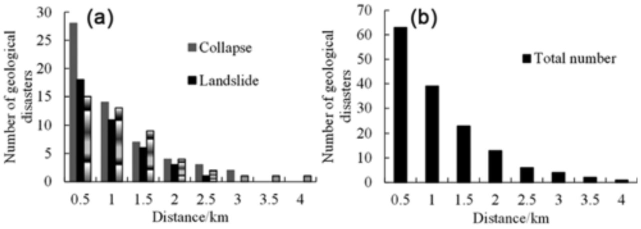

Fig. 7 — The relationship between distance from the bank to (a) geo-hazard type, and (b) total number of geo-hazards

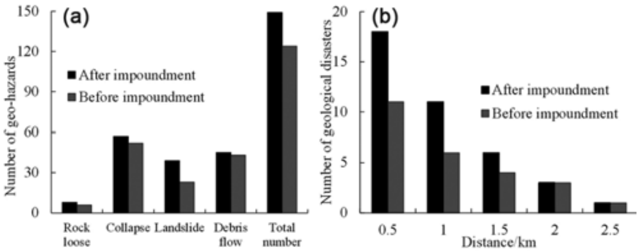

Fig. 8 — Comparison of geological disaster (a) types, and (b) distances from the bank, before and after water storage

Table 4 — Area of geo-hazards in different altitude zones

| Altitude zone (m) | < 2200 | 2200-2500 | 2500-3000 | > 3000 |
|---|---|---|---|---|
| Area of altitude zone (Km$^2$) | 7240000 | 31300000 | 204010000 | 7520000 |
| Percentage of area with different altitude rank(%) | 10.89 | 47.09 | 30.71 | 11.31 |
| Number of geo-hazards | 13 | 73 | 52 | 11 |
| Percentage of number with different altitude rank(%) | 8.73 | 49.0 | 34.89 | 7.38 |
| Density /km$^2$ | 0.79 | 2.43 | 1.67 | 0.83 |

geological disasters occurred, especially reservoir bank landslides. The number of geological disasters was the largest at 0 to 0.5 km from the river, and declined with increasing distance from the river (Fig. 8b). The high incidence of land sliding close to the reservoir can be explained as follows. Firstly, abrupt reservoir water level fluctuation will induce new landslides. Secondly, water level fluctuation will cause groundwater changes adjacent to the reservoir bank, through interactions with rock-soil mass, including physical, chemical, and mechanical functions. Physical functions includes lubrication, softening effects, reinforcement of bound water, and chemical functions, including dissolution, hydration, and hydrolysis. The mechanical effect includes changes in hydrostatic, and flow pressure. In general, groundwater changes will reduce the deformation and strength of rock-soil mass, and will lead to groundwater recharge, runoff, and discharge changes, which will increase the likelihood of geological hazards. Therefore, geological disasters increase after reservoir impoundment, especially landslides, as reservoir water storage increases their incidence in the proximity of the reservoir bank.

### Geotechnical properties and slope structure

The strata on both sides of the reservoir show characteristics of a natural layer, which is the main control plane for slope deformation and failure[9]. River flow direction determines the original bank slope condition, and collapses and landslides are more likely to happen on steep, compared to flat slopes. Moreover, in the reservoir area, the types, development and distribution of geological disasters also have a close relationship with slope body, slope structure, and especially geotechnical liquid properties. For example, steeply-inclined structural, and bedding structural planes control the development of landslides in bedding slopes. Moreover, there are steep-inclined structural planes in the counter-bedding slopes, which will produce collapses. From the field investigation, three types of landslides were also identified, including rock, soil, and gravel soil landslides accounting for 80 %, 15 % and 5 %, of total landslides, respectively. Therefore, landslides and collapses are closely related to the slope body structure, rock mass structure, and a combination of features.

## Discussion

According to detailed field investigation, collapses, landslides and debris flows are the main geological disaster types in the reservoir area, and their formation mechanisms are as follows.

### Landslides

Earthquakes, torrential rainfall, and reservoir water level fluctuations are the main triggers of landslides and collapses in the reservoir area. Due to long-term geological processes, a large number of fractures have appeared in the rock sliding body. Rainfall infiltrates through these fractures, and rapidly saturates the soil water, leading to an increase in the sliding moment increment, reducing landslide stability, and increasing the likelihood of failure. Rain water that infiltrated the landslide body through these fractures during periods of prolonged and periodic intense rainfalls, will simultaneously increase the weight of the landslide, and seepage pressure. Increasing water pressure also decreases the effective stresses on the slip surface, thus resulting in reduced shearing resistance, increased thrust and the splitting effect of fissure water which leads to the cracks being deepened, causing the landslide to deform.

Additionally, earthquakes are an external direct triggering factor for landslides. According to investigation and analysis of the landslides, many are closely associated with earthquakes, Moreover, direct earthquake activity loosens the landslides, reduces their stability and aggravates landslide deformation.

Reservoir water level fluctuations also reduce the stability of landslides as follows. When filling the reservoir, water slowly permeated into the land slide body. The ground water level at the front of the slide was below the reservoir water level, which produced seepage pressure toward the slide, resulting in a stabilizing effect. However, the slip surface softens after being easily saturated due to the loose soils of the lower part of the landslide body, which leads to a decrease in the bond force and friction coefficient between particles. Then, the sliding resistance and shear strength of the sliding zone are reduced. Furthermore, the effective soil weight in the landslide body is changed greatly from its natural weight to float weight, as a result of the pore water pressure being produced. Uplift pressure is then produced in the lower part of the landslide body. Moreover, a higher rate of reservoir water level rise creates a greater difference between the groundwater and reservoir water levels, and greater seepage pressure, thus resulting in larger landslide movement. Therefore, slope stability will be reduced and rapid drawdown will weaken the stability of the landslide. The speed of groundwater descent in the landslide is smaller than the rate of reservoir water drawdown, which leads to excess pore water pressure in the sliding body. Furthermore, dynamic water pressure in the landslide will increase as rapid drawdown occurs, with the landslide sliding towards the reservoir. Then the unloading effect will produce a sliding body and water hammer effect in the cracks, ultimately reducing landslide stability.

### Debris flow

According to our investigation, debris flows include gulch development, and slope liquefaction types. The gulch development type is controlled by a geological environment evolution process, which includes saturation, erosion, migration, flushing, and accumulation for the deposit according to a certain space and time law. This type of debris flow is made of circulation, provenance and accumulation areas. The solid source stems mainly from the loose debris of debris deposits and valley sources from the catchment area on both sides. Basic characteristics include a longer path, greater catchment area, strong destructive ability, cyclic, and usually accompanied by landslide collapse.

The slope liquefaction type of debris flow is induced by continuous heavy rain in steep hilly terrain, forms as a slope rock mass in the slope body and appears as a sudden downward flow due to the rapid saturated liquefaction of the rock mass. This type of debris flow is characterized by large spatial coverage (thousands of square kilometers), small scale, clusters, and great damage. Moreover, it can quickly transform in the same place through a chain reaction that can result in a collapse-landslide-debris flow.

## Conclusion

Our research reveals that slope angle has a strong impact on the development and distribution of geological disasters in the reservoir area, and is optimally expressed for landslides when the slope angle is 30°-50°. Slope aspect also influences the development and distribution of landslides, which are associated more with south and southwest-facing slopes in the reservoir area. Geological disasters are most often found between 2200 and 3000 m elevation, accounting for 83.8 9 % of the total number, and in particular between 2200 and 2500 m. Most landslides were distributed within 3,000 m from the main fault, which is the main control on landslide occurrence up to a certain distance. Close proximity to the river also increases the likelihood of land sliding. Geological disasters increased after reservoir impoundment, especially landslides close to the reservoir banks. Landslides and collapses are closely related to slope body structure, rock mass structure, and combinations of these features. Triggers for landslides include earthquakes, torrential rainfall, and fluctuations in reservoir water level. Rainfall and reservoir water level fluctuations weaken the stability of landslides and facilitate the occurrence of disasters caused by earthquakes. Continuous rainfall or torrential rainfall can induce landslides and collapses, especially debris flows. In our field investigations, we recognized 2 types of debris flow: gulch development and slope liquefaction.

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