Disaster characteristics and cause analysis of railroad slope in complicated and dangerous mountainous areas

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Abstract. With the vigorous development of China’s railroad industry, increased railroad construction has extended to complex and dangerous mountainous areas. During the construction and operation of railroads in this area, various geological disasters are inevitable, bringing significant difficulties to railroad construction and significant threats to personal safety. This study focuses on the typical railroad passing through dense and dangerous mountainous areas as the research object. Through on-site investigations, the characteristics of slope disasters along the railroad were analyzed following the laws of disaster distribution and characteristics of disaster development. The study analyzes the causes of slope disasters by investigating internal and external factors. The research results show that the geological disasters along the railroad can be divided into landslides and collapses, of which there are 8 landslide disasters and 15 collapse catastrophes. Landslides are characterized as creeping and fretting stages according to their development characteristics. Collapses can be divided into four types of dangerous rock masses according to the scale of disaster distribution. Many factors influence the development of landslide geological disasters, and the development of geological disasters is the result of the combined action of multiple influencing factors. By analyzing the slope disaster along the railroad, this study provides an effective reference basis for constructing complex mountain railroads in the future.

1. Introduction

China experiences frequent geological disasters. In engineering construction, many geological disasters induced by man and formed naturally threaten the safety of people’s lives and property[1-5]. On May 12, 2008, the Wenchuan earthquake caused many geological disasters, causing direct economic losses of 150 billion yuan, and 34,073 people were killed. On November 8, 2015, there was a large-scale landslide on National Highway 210, and the accumulation of landslides obstructed traffic and affected traffic safety. On July 24, 2019, a huge landslide occurred in Liupanshui, Guizhou, killing 11 people.

Currently, considerable progress has been achieved in the study of geological disasters. The book Analysis and prevention of landslides provides a reference for treating landslides in China[6]. Zhang Yanyan et al.[7] conducted a landslide stability evaluation built on the analysis of the landslide formation mechanism. The results have a high value in disaster prevention and mitigation. Cheng Qiang et al.[8] studied the development of geological disasters in the Jiuzhaigou Valley Scenic Area.
and guided its reconstruction after the catastrophe. Jie Jing[9] analyzed geological disasters in the Shaxian area to provide reference and basis for the early warning of geological hazards in Shaxian. The above studies have regional characteristics, but no studies have been conducted on the geological catastrophes along the entire railroad in the complex mountainous areas. This study uses mathematical statistics to evaluate geological hazards in the area along the railroad in complex mountainous areas. It serves as a basis for monitoring, and early warning and prevention of the railroad during construction and operation in the future.

2. Geological Overview

2.1. Topography and geomorphology
The area along the route is in an alpine gorge belt, transitioning from the Chengdu plain to the eastern edge of the Tibetan Plateau. It traverses the Longmen, Minshan, West Qinling, and other mountains and crosses the Minjiang, Bailong, and other large rivers. The terrain along the line is strongly cut. The relative height difference of the entire line is more than 1,000 m, and the ground height difference of approximately 200 km is approximately 3,000 m. The overall trend is brought up in the northwest and low in the southeast. The unbroken line crosses the basin area, middle and low mountain area, high mountain area, and plateau area.

![Figure 1](image1.png)

Figure 1 Structural denudation of alpine and valley landforms along the line

2.2. Formation lithology
The area along the line is exposed from the Sinian to the Quaternary, and the main strata are Proterozoic, Paleozoic, Mesozoic, and Cenozoic. It is divided into the quaternary (Q₄), upper tertiary (N₃), upper and lower Cretaceous (K₂, K₁), Jurassic upper-middle and lower series (J₃, J₂, J₁), Triassic upper-middle and lower series (T₃, T₂, T₁), Permian upper and lower series (P₂, P₁), Carboniferous upper-middle-lower (C₃, C₂, C₁), Devonian upper-middle-lower (D₃, D₂, D₁), the Silurian Maoxian Group (Smx), Ordovician middle-lower (O₂, O₁), Cambrian middle-upper system (C₂, C₁), and Sinian upper and lower system (Z₄, Z₃). Granite is distributed in the south-central part of Longmen Mountain and scattered small rock plants are seen in the western Qinling Mountains. Lithology is dominated by phyllite and slate, with sandstone, metamorphic sandstone, limestone, dolomite, shale (with coal seam), and sporadic granite.

2.3. Geological structure
The area along the line is in the clamping area of the western margin of the South China Block, the southwestern margin of the North China block, the eastern margin of the Qinghai-Tibet block, and the
triangular fault block area of northwestern Sichuan. The N-E-oriented Longmenshan Fault zone, near-E-W-oriented west Qinling tectonic zone secondary structural unit Diebu-Bailongjiang Fault zone, and near-S-N-oriented Songpan Ganzi fold tectonic zone secondary structure-Minjiang Fault zone constitute a horizontal A geological structural framework that gradually converges from west to east. Except for the Minjiang Fault, which is approximately 220 km long, the extensions of the Longmenshan Fault zone and Diebu-Bailongjiang Fault are all above 500 km. They are regional active faults with robust earthquake history. They are essential active fault zones in the eastern part of the Qinghai-Tibet Plateau and control the plateau boundaries.

2.4. Hydrogeological conditions

The areas along the line belong to the Yangtze River system, covering the upper reaches of the main rivers such as the Tuojiang, Minjiang, and Jialing rivers. The route runs from the Chengdu Plain to the Longmen Mountain diagonally across the tributaries of the Tuojiang River Basin, Shiting River, Mianyuan River, and Ganhezi River. The Longmen Mountain north of the Chuanzhu Temple is the Minjiang River Basin. North of the Chuanzhu Temple, Hadapu is the tributary of the Jialing River Basin, Heihe, and Bailongjiang. The types of groundwater in the area are pore water of quaternary loose layers, bedrock fissure water, and carbonate karst water. The quaternary loose pore water is distributed in the quaternary loose pile accumulation layer on both sides of the river in the area, the pore water is stored, the water richness is good, and is widely distributed in the plains and narrow mountain valley first-level terraces. Bedrock fissure water is divided into sedimentary rock fissure pore water and magmatic rock fissure water depending on the occurrence conditions of groundwater and lithologies. Sedimentary rocks are composed of sandstone and shale coal-bearing structures. The fissure has excellent water storage. The magmatic rock fissure water is composed of granite and diorite, and the water richness and degree of development of the rock mass fissures vary. The distribution of karst water in carbonate rocks is relatively wide. Because of the various parts of the formation, chemical composition, and percentage of clastic rocks, the water richness is uneven.

3. Slope Disaster Development Law And Characteristics

3.1. Slope disaster distribution law

According to this survey, geological disasters within 1 km around the area along the line include two types of landslides and collapses.

3.1.1. Disaster type

In total, 23 geological disasters in the area along the line exist. Table 1 shows the proportion of landslide and collapse disasters. Among them, collapse disasters are the principal ones, accounting for 65.22%, and landslide disasters are 34.78%.

| Disaster type | Landslide | Collapse |
|---------------|-----------|----------|
| Quantity      | 8         | 15       |
| Percentage    | 34.78%    | 65.22%   |

3.1.2. Landslide scale

Divide the scale of landslide disaster according to the volume and obtain the distribution of landslides of different scales. Table 2 shows that the landslides in the area along the line are predominantly small and medium-sized, accounting for 87.5% of the landslides. One large landslide occurred.
Table 2. Standards and statistics of landslide scale division

| Scale level   | Huge scale | Large scale | Medium scale | Small scale |
|---------------|------------|-------------|--------------|-------------|
| Landslide volume/ m³ | >200 | 100–200 | 10–100 | 10< |
| Quantity      | 1 | 0 | 4 | 3 |
| Percentage    | 12.5% | 0 | 50% | 37.5% |

3.1.3. Collapse type

Depending on the characteristics of avalanche rocks, they can be subdivided into large block caving-type dangerous rock bodies, solitary stone groups, and live rock pile-type dangerous rock bodies\(^{[14-15]}\). Collapse disasters are now classified according to their distribution. Table 3 shows that large-scale fall disasters account for 46.7%, and solitary group collapse disasters account for 53.3%. The probability of occurrence of the two catastrophes is similar.

Table 3. Types and statistics of collapse distribution

| Characteristic                        | Distribution type                                                                 |
|---------------------------------------|-----------------------------------------------------------------------------------|
|                                       | Large block caving-type the location is high and steep, large in volume, and partially buried underground. | Solitary stone group type floating on the slope surface, sheet-like distribution. |
| Quantity percentage                   | 7                                                                                 | 8                                                                                 |
|                                       | 46.7%                                                                             | 53.3%                                                                            |

3.2. Geological hazard development characteristics

3.2.1. Characteristics of landslide development

Studying the material composition of landslides shows that soil landslides are the main ones and rock landslides are relatively rare. The main components of soil landslides include silt clay, gravel soil, coarse breccia soil, and mass rock and soil. The failure mode of landslides shows that traction landslides are mainly used, and the control effect of slope structure types on landslides is not obvious. Evaluating the division of different development stages in the development process of landslides, landslide sliding is divided into six developmental stages, namely, the creeping, extrusion, fretting, sliding, large movement, and consolidation stages. According to their respective development characteristics, the landslides along the line are in the creeping stage of H₁–H₇ and the fretting stage at H₈\(^{[10-13]}\).

The main characteristics of the H₁ landslide are that the boundary of the rear edge of the slope body is a lower platform ridge, and a gentle slope behind the slope body shows multiple creep slip and tensile crack deformation on the ground. Three springs are in the front edge of the slope with a strong flow rate, and Sabre trees are present on the slope surface. The major features of the H₂ and H₃ landslides are the presence of tensile cracks on the trailing edge, sparse surface vegetation on the slope surface, predominantly weeds and small shrubs, and trees on the ridge. The major features of the H₄ landslide are the local destruction of the shallow surface layer near the entrance of the front edge, tensile cracks expanding in the middle of the side, and local slippage. On the H₅ landslide, the landslide is partly reclaimed as dry land, the slope is undulating, and is currently in a relatively stable state.
The local collapse caused by the cutting of the front edge of the slope body and erosion of the surface gullies on the slope body during the construction of the original national highway constitutes the main features of the H6 landslide.

The H7 landslide’s trailing edge is relatively gentle and slightly undulating. Majority of the slopes are shrubs and pine trees, and no obvious cracks are found.

The main feature of the H8 landslide is that the trailing edge has reversed downward fissures, with intermittent radial cracks, and the leading-edge slope also partially collapses.

![Figure 2](image1)

**Figure 2** There is a sloping forest and river at the foot of the slope

![Figure 3](image2)

**Figure 3** Slope cracks

| Number | Length/m | Width/m | Thickness/m | Volume/m³ | Scale       |
|--------|----------|---------|-------------|-----------|-------------|
| H₁     | 800      | 500     | 30          | $600 \times 10^4$ | Huge scale |
| H₂     | 115      | 75      | 10          | $8.6 \times 10^4$  | Small scale|
| H₃     | 70       | 60      | 15          | $6.3 \times 10^4$  | Small scale|
### 3.2.2. Collapse development characteristics

From the material composition of the collapses, rock collapses occur most frequently, and soil collapses are relatively rare. The principal components of rock collapse include sandstone, limestone, slate, and phyllite, and the weathering degree is high in some areas. The failure mode of the collapse shows that the main types are tensile fall, discontinuous collapse, and slip collapse. In some areas, the degree of joint fractures is high, providing conditions for the occurrence of collapse.

In total, 15 dangerous rock mass collapse areas along the line occur, which can be roughly divided into four categories according to the type of dangerous rock mass. Among them, six dangerous rock masses bare hard rock and cliffs, and seven dangerous rock masses bare dangerous rock masses with steep slopes. The remaining two dangerous rock masses belong to the broken steep slope-based hard rock mass and ridge-peak hard rock mass.

The major features of the exposed hard rock dangerous rock masses of cliffs are steep mountain slopes and developed joint fissures. The slope rock masses are blocks of varying sizes, accompanied by sporadic rolling stones and small-scale collapses (Figure 4a).

The main features of the exposed dangerous rock mass of steep slope soft rock are steep terrain and slope, the surface layer is disintegrated and exfoliated, the lower rock layer forms a cavity, and the upper rock layer is suspended (Figure 4b).

The major features of the exposed steep rock masses on broken steep slopes are loose surface slopes, uneven slopes, bending and cracking failures, small-scale falling blocks, and local instability (Figure 4c).

The main characteristics of the ridge-peak hard rock dangerous rock mass are steep mountain, developed joint fissures, and severe weathering (Figure 4d).
4. Analysis Of The Cause Of Slope Disaster

4.1. Internal factor

4.1.1. Topography and geomorphology

The surface is formed by the erosion of the cutting water or free surface caused by excavating the slope. Under the gravity of the upper accumulation layer, the lower part is destabilized and collapses. Along the railroad, the terrain is strongly cut, the valley is vertical and horizontal, and the ground is undulating. The height difference of the entire line is greater than 1,000 m, belonging to the deep erosion landform of the alpine valley. Furthermore, the gullies are prepared in some areas, and the slope is cut noticeably. Under the influence of other factors, it is easy to form geological disasters such as landslides and collapses.

4.1.2. Formation lithology

Formation lithology is the material basis for developing geological hazards, and to some extent controls the susceptibility of geological hazards. If the lithology of the stratum varies too much, the shear resistance of the slope will be lowered, and landslides, collapses, and other disasters will occur. The strata along the line are complex and changeable and exposed from the Sinian to the quaternary. It is dominated by phyllite and slate, with sandstone, metamorphic sandstone, limestone, dolomite, shale (with coal seam), and sporadic granite. Some rock masses have more developed joints with softer rock quality and easy weathering. Under the influence of other factors, for the weak interlayer strata in some slopes along the line, the watery layer softens easily, forming a potential slip surface, and finally, landslide. Simultaneously, areas with a high weathering degree on some slopes along the line and poor physical and mechanical properties of the surface soil could also cause the occurrence of landslide hazards.

4.1.3. Slope angle

The slope angle is a principal factor affecting the stability of the slope. It directly determines the stress distribution of the slope, which has a definite impact on the stability of the slope. When the angle range is 40°–50°, the development degree of a geological disaster is highest. As the angle increases, the degree of progress of geological disasters has weakened. The angle of geological disasters in the
area along the line is between 30°–70°. It has the angle conditions for developing geological catastrophes.

4.1.4. Geological structure

The area along the line crosses the Minjiang River, Longmen Mountain, and several other fault zones. Consequently, the slope structure along the line is complicated, the stratigraphic occurrence is variable, the rock mass is broken, the joint fissures are developed, and structures such as syncline, anticline, and fold are formed, increasing the degree of rock fragmentation in the area along the line and reducing the integrity of the rock mass. Weathering and flaking will increase, thereby reducing the stability of the slope. Under other factors, geological disasters such as landslides and collapses are easy to form.

4.2. External factors

External factors are the direct inducement of geological disasters, including rainfall, earthquakes, and artificial disturbances.

4.2.1. Rainfall factor

Rainfall is a principal inducing factor of geological disasters. The impact of precipitation on slope stability manifests as precipitation along joints and crack infiltration or crack filling, increasing the static and dynamic water pressure in the slope body. Precipitation stays in the rock pores, forming pore water pressure, softening slope soil, and reducing soil strength. Precipitation infiltrates the aquifer and enriches, resulting in buoyancy, and increases the water content of the slope body, increasing the weight of the slope body and the sliding component of the slope body\[18\]. The annual rainfall in some areas along the route is 500 mm–900 mm, and the average rainfall over 30 years is 731 mm. The rainy season is from June to September, predominantly heavy rain and showers. It has rainfall conditions for developing geological disasters.

4.2.2. Earthquake factor

Earthquakes are among the main inducing factors of geological disasters, subjecting the slope body to vertical and horizontal forces. The internal stress balance of the slope is broken, the slope body loses stability, tension cracks and slides are generated, and finally, geological catastrophes occur, such as collapse and landslides\[19\]. Two large earthquakes have recently occurred in the area along the route, namely the Wenchuan earthquake with magnitude 8.2 and the Jiuzhaigou earthquake with magnitude 7. Both earthquakes caused geological disasters such as falls and landslides. The area along the line has seismic conditions for developing geological disasters.

4.2.3. Artificial disturbance

Human engineering activities change the original terrain and destroy surface vegetation, breaking the singular stress balance inside the slope, and eventually, a geological disaster occurs. Most railroad construction along the line is through mountainous areas. The geological conditions are complex, and the construction of tunnels and bridges is challenging, damaging the original slope during the construction process. When the protective measures do not achieve effective protective effects, geological disasters such as collapses and landslides are triggered.

5. Conclusion

The development characteristics of geological hazards along the line were investigated and analyzed, and an analysis of the mechanism of geological hazards in the area was conducted. The following conclusions were drawn.
The geological disasters in the area along the route are classified as landslides and collapses. The area experienced 15 collapse disasters, including 7 large-scale avalanches and 8 boulder groups collapses, and 8 landslide disasters, including 7 small and medium landslides and 1 large landslide. Collapse disasters are predominantly rock collapses, and the failure modes include tensile, discontinuous, and sliding collapses. The landslide disasters are dominated by soil landslides, and the failure mode is traction landslides. The landslide disasters along the line are in the creeping and fretting failure mode.

6. References

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