

Analysis of Development Characteristics and Influencing Factors of the Resuo Rockfall at Gyirong Port, Tibet, along National Highway G216 (Postprint)

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Date: 2025-07-22T00:00:00+00:00

Abstract

Since the Nepal “4.25” earthquake, the G216 National Road at Gyirong Port in Gyirong County, Tibet Autonomous Region has frequently experienced large-scale, high-impact, high-position concealed rockfall disasters, with the Resuo rockfall being a typical case. The Resuo rockfall is a high-position rockfall that is difficult to identify through conventional means, and monitoring methods struggle to provide early warning. It currently poses a serious threat to the normal operation of the China-Nepal trade corridor, causing severe casualties and property losses for people of both countries. Based on the characteristics of existing rockfall disasters, this study analyzes the development features, influencing factors, and distribution patterns of rockfalls, thereby providing a theoretical basis for disaster prevention and mitigation of regional rockfall hazards. The research results indicate that the Resuo rockfall area contains 2 dangerous rock zones, including 86 individual unstable rock masses, 20 fracture zones, and 12 slope rolling stones. The slopes of unstable rock masses exhibit severe denudation, with highly fractured surface rock and well-developed joints and fissures. The spatial morphology of individual unstable rock masses is predominantly “blocky or slab-like”, with a few being “irregular or wedge-shaped”. The failure modes are mainly sliding and toppling, with a small amount of falling. Topography and geomorphology, stratigraphic lithology, and geological structure are internal factors in rockfall formation, exerting a controlling influence on the formation and development of unstable rock masses; weathering, vegetation root wedging, and earthquakes are external factors, exerting a promoting influence on the formation and development of unstable rock masses.

Full Text

Preamble

Development Characteristics and Influencing Factors of Resuo Collapse on G216 National Highway at Gyirong Port, Tibet

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Abstract

Since the “April 25” earthquake in Nepal, the G216 National Highway at Gyirong Port in Gyirong County, Tibet Autonomous Region has frequently experienced large-scale, high-impact, high-altitude, and concealed collapse disasters, with the Resuo collapse being a typical example. The Resuo collapse is a high-altitude rockfall that is difficult to identify through conventional methods and challenging to monitor for early warning. It currently poses a severe threat to the normal operation of the China-Nepal trade corridor and has caused considerable loss of life and property for both nations. Based on an analysis of existing collapse disaster characteristics, this study examines the developmental features, influencing factors, and distribution patterns of such collapses, thereby providing a theoretical foundation for regional disaster prevention and mitigation efforts. The results indicate that the Resuo collapse area contains two hazardous rock zones, encompassing 86 dangerous rock units, 20 fractured zones, and 12 slope rolling stone areas. The unstable rock mass exhibits severe surface denudation, highly fractured rock, and well-developed joints and fissures. The spatial forms of dangerous rock units are predominantly “blocky or slab-like,” with a smaller proportion being “irregular or wedge-shaped.” Failure modes are primarily sliding and toppling, with fewer instances of falling. Topography, stratigraphic lithology, and geological structure serve as internal causes of collapse formation, playing a controlling role in the development of hazardous rocks. Weathering, vegetation root splitting, and seismic activity act as external factors, promoting the formation and progression of hazardous rocks.

Keywords: Gyirong Port in Tibet; Highway G216; Lithogenic collapse; Development characteristics; Influencing factors

Introduction

At 14:11 on April 25, 2015, a magnitude 8.1 earthquake struck Pokhara, Nepal (28.2°N, 84.7°E) at a depth of 20 km, approximately 200 km from Kathmandu and only 30 km from Gyirong Port (Zhu et al., 2017). Affected by this “4.25” earthquake, the road section of National Highway G216 from Gyirong Town to

Gyirong Port suffered severe damage, with frequent geological disasters including landslides, collapses, and debris flows causing roadbed subsidence, collapse, and even complete blockage in some sections. The Resuo collapse, located along the G216 National Highway from K3525+600 to the Gyirong Port border gate, has become particularly hazardous, seriously threatening the safe operation of the China-Nepal trade corridor with potential property damage exceeding 200 million yuan.

Collapse is a common geological disaster in mountainous areas, characterized by significant concealment, strong suddenness, high randomness, rapid speed, and violent occurrence (Wang et al., 2024; Su, 2011). Understanding the influencing factors of collapse is fundamental to studying regional collapse characteristics and a prerequisite for accurately judging the development features and disaster-prone areas of dangerous rocks. Inducing factors are crucial for collapse development. Through practical engineering investigations, Hu (1985) and Xu et al. (2008) explored the formation conditions and mechanisms of collapse disasters, revealing a series of complex inducing factors during collapse development and laying a foundation for subsequent research. The causes of dangerous rock collapse are complex and multifaceted. The Resuo collapse is located in an area of intense uplift on the Tibetan Plateau, affected by complex geological structures and steep mountain topography, which creates significant obstacles for regional collapse research. Currently, relevant studies in this area remain blank. Therefore, this paper comprehensively analyzes the inducing factors of the Resuo collapse disaster based on the region's unique topography, lithology, geological structure, rainfall, weathering, vegetation root splitting, seismic activity, and human engineering activities, providing new insights for geological disaster prevention and control in this area.

2.1 Geological Background

The study area geographically spans the eastern section of the Gangdise Mountains and part of the Himalayan range, belonging to the North Himalayan tectonic belt where faults and folds are well developed. The main faults and folds are as follows:

Tuodan-Nila Fault Zone (F1): This fault zone forms the boundary between the North Himalayan tectonic belt and the High Himalayan tectonic belt. The north side consists of Sinian-Cambrian systems and partial Paleozoic strata, while the south side comprises pre-Sinian systems. The fault strikes nearly east-west with undulating extension, dipping northward with variable angles (10° – 65°). The upper plate (north side) Rouqiecu Group or Jiacun Group exhibits extremely developed folding and fragmentation due to strong thrusting, while the lower plate (south side) contains muscovite granite gneiss intrusions, likely products of the Hercynian movement. The fault zone subsequently experienced multiple inherited activities, particularly during the Himalayan movement, causing widespread mylonitization and mineral recrystallization along the rock mass. Tension phenomena derived from thrusting can sometimes be observed along the

fault zone, which may have formed along the unconformity between pre-Sinian and Sinian-Cambrian systems (Chen, 2014).

Chimadun-Duoqingcuo Fault Zone (F2): This fault zone divides the Dingri-Gamba subzone from the Laguigangri subzone. Its strike gradually changes from NWW in the western section to nearly east-west, with the eastern end deflecting to NEE and connecting to granite bodies at the China-Bhutan border. The main fault plane dips northward at 30° - 50° , clearly controlling lithofacies changes in Mesozoic-Cenozoic marine sediments on both sides. Numerous hot springs occur near the fault zone (in the Gamba area), indicating a reverse (thrust) fault. Geophysical exploration suggests it is a deep fault.

Xiabala-Zangla Composite Anticline: Extending 270 km in NWW-EW direction with a width of 20-40 km, its core and southern wing consist of J3w, while the northern wing comprises K1j. The northern wing dips at $310^{\circ} < 49^{\circ}$, while the southern wing dips southward at moderate angles. A series of small Himalayan period rock bases are distributed along the axis. The April 1960 M4.75 earthquake occurred at the northwest corner of the Peikucuo anticline axis.

Mula-Longma Anticline: This anticline extends 130 km in an EW arc with a width of 20 km, with J3w in the core and K1j in the wings, forming a gentle arc bulging southward and dipping westward. An M6.25 earthquake occurred in 1931 near the intersection of the 89° E longitude line with the axis.

[Figure 1: see original paper] Geological Structure Map of the Study Area

2.2 Topography and Geomorphology

The study area is located on the left bank of the Gyirong Zangbo River valley, characterized by medium-high mountain gorge landforms. Glacial cutting has created numerous high and steep terrains in the region. The collapse occurs on a slope with steep gradient, large elevation difference, and favorable free-face conditions, providing topographic conditions for collapse (dangerous rock) generation. Steep terrain is essential for dangerous rock formation. The overall slope gradient of the Resuo collapse development area ranges from 42° to 60° , with local bedrock cliff angles of 70° - 85° . These high and steep topographic conditions provide favorable space for deformation and instability of dangerous rock zones. The rock mass undergoes unloading stress release toward the free face, after which rock layer stress within the slope readjusts, generating toppling tension cracks and deformation toward the free face. As deformation time increases, tension cracks gradually extend deeper, forming a distribution pattern of fractured (broken rock mass) \rightarrow relatively fractured (block-fractured rock mass) \rightarrow relatively intact (bedrock) from top to bottom. With further intensification of weathering, erosion, and other geological processes, stress adjustment and accumulation accelerate, tension cracks further expand, and gradually develop deeper, ultimately completing the 贯通 (connection) of the entire fracture surface (Liu, 2018).

2.1 Rainfall

The study area has an average annual temperature of 9.54°C, with maximum and minimum average temperatures of 22.43°C and -0.51°C, respectively. The average annual cumulative rainfall is 842.2 mm, with maximum monthly cumulative rainfall occurring in July and August (162.45 mm and 176.85 mm, respectively). Minimum cumulative rainfall occurs in November and January (6.45 mm and 7.9 mm, respectively). From September 26 to 29, 2024, continuous heavy rainfall and snowfall caused road blockage on National Highway 216 (Gyirong County to Resuo Bridge) due to debris flows, washed-out roadbeds, landslides, and other natural disasters, severing the connection between Gyirong Town and Resuo Bridge.

3.1 Distribution Characteristics

The Resuo collapse is located along G216 National Highway from K3525+600 to the Gyirong Port border gate, with central coordinates at 85°22'41.90" E, 28°16'49.75" N. The study area is bounded by the Gyirong Zangbo River to the southwest, Donglin Zangbo River to the southeast, mountain ridge to the northeast, and gully to the northwest. The dangerous rock zone measures approximately 500 m longitudinally, 700 m transversely, with a total area of about 0.35 km². The collapse boundary is clear, with vegetation coverage within the collapse area relatively low at approximately 20%.

The Resuo collapse has an overall elongated planar shape, divided into two dangerous rock zones: southeastern and southwestern. The slope aspect ranges between 140°-230°. The top elevation of the dangerous rock zones ranges from 2400-2610 m, while the bottom elevation ranges from 1820-1830 m, with relative height differences of 170-780 m.

[Figure 2: see original paper] Panoramic View of Dangerous Rock Zone I
[Figure 3: see original paper] Panoramic View of Dangerous Rock Zone II

3.2 Collapse Types and Development Characteristics

The Resuo collapse area contains 86 dangerous rock units, 20 fractured zones, and 12 slope rolling stone areas. The rock slope surface exhibits severe denudation, with highly fractured rock mass and well-developed joints and fissures. Individual dangerous rock volumes range from 2.7-4756.5 m³, with a total volume of 99,250.67 m³. The spatial forms of the 86 dangerous rock units are predominantly “blocky or slab-like,” with a smaller proportion being “irregular or wedge-shaped.” Failure modes are primarily sliding and toppling, with fewer falling cases. Specifically, there are 40 sliding-type, 36 toppling-type, and 10 falling-type units.

Statistical Table of Resuo Collapse Characteristics / ($\times 10^4$) m³

1. Typical Sliding-Type Dangerous Rock (WY8): Located in the middle of Dangerous Rock Zone I of the Resuo collapse, WY8 has free faces on both

sides and at the front edge. The rock unit has a top elevation of 2012 m, bottom elevation of 1978 m, and relative height difference of 32 m. It is approximately 13–16 m wide transversely (average 14 m), with an average thickness of about 5 m and volume of approximately 163.4 m³, classifying it as a small dangerous rock mass. The lithology is granite gneiss with an attitude of 52° 61°, presenting a “rectangular” spatial form. The failure mode is sliding, with a main collapse direction of 156°.

Field investigations reveal that the rear of the dangerous rock mass is controlled by unloading cracks trending NW-SE, extending approximately 1–2 m with opening widths of 1–2 cm and spacing of 1–3.5 m. The fracture surfaces are relatively straight, slightly rough, with an attitude of 230° 62° and no infilling. Both sides and the front are free faces. The base rock mass is thin-layered and relatively fractured. The cliff overall forms a reverse slope. The dangerous rock mass is controlled by bottom fracture surfaces and rear unloading cracks. Under heavy rainfall conditions, the bottom fracture surface is prone to softening, potentially causing sliding failure along this plane.

2. Typical Falling-Type Dangerous Rock (WY54): Located at the top of Dangerous Rock Zone II, WY54 has a free left side, suspended lower portion, and right boundary defined by developed fissures. The rock unit has a bottom elevation of 2037.3 m, top elevation of 2065.0 m, relative height difference of 27.7 m, average width of 15.0 m, average thickness of about 5.5 m, and volume of approximately 1367.3 m³, classifying it as a medium dangerous rock mass. The lithology is granite gneiss with an attitude of 47° 55°, presenting a “blocky” spatial form. The failure mode is falling, with a main collapse direction of 225°.

Field investigations show that the rear edge is controlled by bedding fissure L2: 95° 48°, extending approximately 15–20 m with opening widths of 3–5 cm, clay filling, and spacing of 10–15 m. The fissure surfaces are rough with no obvious interlayer dislocation between the front and rear rock masses. The cliff overall forms a reverse slope. The dangerous rock mass is controlled by rock bedding and outward-dipping fissures, which may cause the rock mass center of gravity to tilt outward, inducing falling failure.

[Figure 4: see original paper] Typical Sliding-Type Dangerous Rock

[Figure 5: see original paper] Typical Falling-Type Dangerous Rock

3. Typical Toppling-Type Dangerous Rock (WY27): Located in the middle-lower portion of Dangerous Rock Zone II, WY27 has free faces on both left and right sides. The rock unit has a bottom elevation of 1843.8 m, top elevation of 1876 m, relative height difference of 32.2 m, average width of about 21 m, average thickness of about 4.3 m, and total volume of 1564.6 m³, classifying it as a medium dangerous rock mass. The lithology is granite gneiss with an attitude of 50° 58°, presenting a “blocky” spatial form. The failure mode is toppling, with a main collapse direction of 233°.

Field investigations indicate that the rear is controlled by unloading cracks extending approximately 10–20 m with opening widths of 50–60 cm, no filling,

spacing of 5–8 m, and rock debris infilling. Both sides and the front are free faces. The base rock mass is thin-layered gneiss, relatively fractured, with a concave cavity formed below. The cliff overall forms a reverse slope. The dangerous rock mass is controlled by bottom fracture surfaces and rear unloading cracks. Under heavy rainfall conditions, the bottom fracture surface is prone to softening, potentially causing toppling failure.

[Figure 6: see original paper] Typical Toppling-Type Dangerous Rock

[Figure 7: see original paper] Typical Slope Rolling Stone

4. Typical Slope Rolling Stone (GS3): Located at the slope bottom with a gradient of about 45° , the dangerous stone foundation consists mainly of blocks with only a small portion buried below the slope surface. Most of the outer foundation has been undercut and suspended, with a fissure developed in the middle dividing the dangerous stone into two halves hanging above the inner slope top of the highway. Under heavy rainfall or earthquake conditions, instability and rolling may occur, qualitatively determined as a quasi-stable state. It primarily threatens the highway, passing vehicles, and the proposed border trade market.

5. Typical Fractured Zone (PS04): The fractured zone is approximately 40 m longitudinally, 20 m transversely, with a relative height difference of about 30 m. Field investigations indicate an average thickness of about 4 m for the fractured rock mass, with individual volumes ranging from $3.2\text{--}12.5\text{ m}^3$ and total collapse volume of approximately 2000 m^2 .

[Figure 8: see original paper] Typical Fractured Zone Dangerous Rock

4 Analysis of Influencing Factors in the Study Area

The formation factors of the Resuo collapse on G216 National Highway at Gyirong Port are primarily natural, including topography, stratigraphic lithology, geological structure, rainfall, weathering, vegetation root splitting, and seismic activity. Among these, topography, stratigraphic lithology, and geological structure are internal causes and dominant factors that control the formation and development of dangerous rocks. Weathering, vegetation root splitting, and earthquakes are external causes and inducing factors that promote the formation and development of dangerous rocks.

4.1 Elevation Characteristics

Huang et al. (2009, 2013) and Zhang et al. (2011) have identified elevation as an important factor affecting the occurrence and distribution of geological disasters. The Resuo collapse has a large elevation difference, with dangerous rock zone tops ranging from 2400–2610 m and bottoms from 1820–1830 m. As shown in Table 2, collapse distribution gradually increases with elevation, peaking at the slope top. This occurs because increased slope height leads to greater stress and potential energy, facilitating collapse occurrence. Additionally, Gyirong is

significantly affected by earthquakes. Research indicates that upper ridge crests and isolated or multi-free-face mountain bodies in canyons are most sensitive to seismic waves. During propagation, seismic waves undergo topographic amplification effects, reflecting multiple times on mountain bodies, with seismic acceleration values at higher elevations greater than at slope toes, leading to frequent collapses at slope shoulders and tops (Tang et al., 2024).

Elevation Distribution Statistics of Resuo Collapse: 1800-2000, 2000-2200, 2200-2400, 2400-2600

4.2 Lithology Influence

The collapse rock in the study area consists of Pre-Sinian Nyalam Group (AnZn1) schist, gneiss, and migmatitic gneiss. These rocks are primarily composed of layered silicate minerals such as mica (biotite, muscovite), chlorite, and talc. These minerals have layered crystal structures that align along directional pressure during metamorphism, forming prominent foliation. The bonding force between foliation planes is weak (especially for mica minerals), causing rocks to easily split along foliation planes and form natural fracture surfaces. Additionally, schist often mixes hard minerals (quartz, feldspar) with soft minerals (mica). The significant differences in hardness and deformation capacity among different minerals easily produce differential fracturing under stress, exacerbating overall fragmentation.

4.3 Rock Mass Structure

Statistical investigations show that regional tectonic activity generates high in-situ stress, promoting stress concentration in canyon rock masses and creating various exogenic structural planes. The study area has well-developed joints and fissures, primarily two sets: L1 (200° - 230° 42° - 75°) and L2 (310° - 330° 72° - 83°), with slope aspects of 215° - 245° 40° - 60° . Under oblique cutting by the main controlling fissure L1 and near-perpendicular intersection of fissure L2 with the slope surface, the combined action of L1, L2, and bedding planes cuts the rock mass into blocks, developing numerous joints that divide the rock mass into dangerous rock blocks of various sizes and shapes. When the combination relationship of structural planes is unfavorable for stability, failure easily occurs.

4.4 Seismic Influence

Seismic activity accelerates the development and formation of dangerous rocks. When seismic forces propagate through rock masses, they generate repeated tension-compression and shear stresses, accelerating the expansion of existing fissures and creating new ones. High-frequency vibration from seismic forces causes micro-damage accumulation inside rocks, reducing rock mass strength. Seismic action weakens existing structural planes, causing dislocation or opening of existing bedding planes, joints, and fissures, reducing friction and cohesion between structural planes and providing water-filling space for fissures, leading

to sudden pore water pressure increase and reduced effective stress. Seismic action can also directly trigger dangerous rock failure. For rock masses in critical equilibrium, seismic forces increase the downward driving force, directly causing failure.

4.5 Climate Influence

(1) Precipitation: High-intensity short-duration rainfall rapidly infiltrates rock and soil masses, increasing water content, self-weight, and sliding force. Water filling fissures creates upward buoyancy, reducing effective stress, weakening shear strength, and decreasing fissure plane friction coefficients (Lü et al., 2022).

[Figure 9: see original paper] Rose Diagram of Collapse Joint and Fissure Orientations

[Figure 10: see original paper] Relationship Between Rainfall and Collapse Disaster Development

(2) Temperature Variation: The Resuo collapse is located in a high-altitude area. Large temperature differences and frequent freeze-thaw cycles occur in winter. Water infiltrating fissures freezes and expands by 9%, generating expansion pressure that causes fissure expansion (Ye et al., 2021). After ice melts, fissure space temporarily enlarges, accelerating subsequent water infiltration. Additionally, temperature differences cause differential expansion between rock surface and interior, creating micro-fissure networks. Differences in thermal expansion coefficients among various minerals lead to internal stress accumulation and eventual disintegration.

Conclusions

- (1) The Resuo collapse is located on G216 National Highway at Resuo Village, Gyirong Port, Gyirong County, Tibet Autonomous Region. The area contains two dangerous rock zones, including 86 dangerous rock units, 20 fractured zones, and 12 slope rolling stone areas. The rock slope surface exhibits severe denudation, highly fractured rock, and well-developed joints and fissures. The spatial forms of dangerous rock units are predominantly “blocky or slab-like,” with a smaller proportion being “irregular or wedge-shaped.” Failure modes are primarily sliding and toppling, with fewer falling cases.
- (2) In the study area, topography, stratigraphic lithology, and geological structure are internal causes and dominant factors that control the formation and development of dangerous rocks. Weathering, vegetation root splitting, and earthquakes are external causes and inducing factors that promote the formation and development of dangerous rocks.
- (3) For overhanging, isolated, loose dangerous rocks and quasi-stable slope rolling stones in the study area, manual clearing is recommended. For

relatively fractured dangerous rock masses (zones), active and passive nets can be used for treatment. For dangerous rock masses with large areas that may form cavities, cavity sealing + embedding treatment can be applied.

- (4) Professional monitoring of disaster points is recommended to timely understand disaster development trends and adopt engineering measures for prevention and control.
- (5) This study analyzes the structural characteristics and formation mechanism of the Resuo collapse, filling the data gap for subsequent geological disaster prevention and control work.

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