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Research on catastrophic rock avalanche at Guanling, Guizhou, China

Abstract On June 28, 2010, a catastrophic rock avalanche occurred after an extreme rainstorm at Guanling with N 25°59′10″ in latitude and E 105°16′50″ in longitude, Guizhou, China. This rock avalanche has a long run-out distance of 1.5km, with 1.75 million cubic meters of debris instantly burying two villages and resulting in 99 deaths. It originated in the coal measure strata, with the upper part of limestone and dolomite, the middle part of the sandstone with gentle inclination, and the lower part of shale and mudstone, together locally with coals. This kind of unique structure, with hard resistant caprock overlying softer ductile rocks, coupled with the central outflow region at the contact zone, has catastrophic potential for rock avalanches and creates challenges for engineering geological/hydrogeological analysis. The topography showed that the hillside slopes were steeper at the upper portion but gentler in the lower portion, looked like the shape of a "boot." The upper steep landform easily led to slope instability due to its high static shear stresses, and the wide middle and lower parts provided kinematic conditions for long run-out. Transformation of the larger potential energy into kinetic energy contributed to the formation of a rapid long run-out rock avalanche. The rainfall from June 27 to 28 was the apparent trigger of this catastrophic avalanche. The measured rainfall of more than 310mm within 24h exceeded the local historical records that were recorded over the last 60 years. The pore pressure on discontinuities of sandstone had an effect on the slope stability. The valley runoff supplied a saturated base for the long run-out debris, inducing an additional increase of the terminus distance and the increased velocity of the avalanche movement.

Keywords Rock avalanche · Debris flow · Rapid long run-out · Guanling

Introduction

On June 28, 2010, a catastrophic rock avalanche occurred after an extreme rainstorm at Guanling with N 25°59′10″ in latitude and E 105°16′50″ in longitude, Guizhou, China. This rock avalanche has a long run-out of 1.5 km, with 1.75 million cubic meters of debris burying two villages and resulting in 99 deaths (Fig. 1). After the mass slid down toward the NW, of some 500 m, the slide mass of about 1.15 million cubic meters scraped and greatly impacted the opposite slopes causing 21 households to be destroyed. With a deflection of 90°, the rock avalanche transformed into a rapid debris flow and quickly slid further down for about 1,000 m. The slide mass volume was increased by material entrainment of the surface deposits in Dazhai Village, and 16 households were destroyed.

Investigation shows that the extreme rainfall was the main triggering factor for the catastrophic rock avalanche. Within 24 h from June 27 to 28, the rainfall was up to 310 mm. Between the hours of 8:00 to11:00 P.M. on June 27 (15 h before the occurrence of avalanche), the rainfall amount had already risen to 237 mm, which exceeded the local historical records over the last 60 years.

Increasing population density and development of mountainous terrain bring human settlements within reach of landslide hazards. Perhaps the most serious threat arises from small, high-frequency landslides such as debris flows and debris avalanches. Large and relatively rare rock avalanches also constitute a significant hazard, due to their immense capacity for destruction making assessment of rapid long run-out events, a crucial undertaking (Hungr 2006).

In recent years, with the shortening of return periods for severe weather events such as heavy rainfall, catastrophic landslides have resulted in large-scale casualties due to the resulting increased occurrences of rapid long run-out rock avalanches, especially in China (Yin 2009). Therefore, investigation and mitigation of such disasters must become a critical aspect for determining safe distance for locating house and infrastructure, and determining the extent and timing of evacuation and warnings.

Geological settings and weather

The area where Guanling rock avalanche occurred has an elevation of 800–1,500 m asl. It is also characterized by an uplift-erosion topographical process that includes the chemical and mechanical weathering of the rock. This type of topography is generated by a combination of crustal uplift, river erosion and down-cutting. The cutting depth of the river valley ranges from 500 to 1,000 m that is often characterized as canyon and ravine. The area near the watershed at the top edge of the valley features remnants of ancient karst, and the vertical karst topography is most developed in the mountains.

The rainfall in this area is abundant, with an average annual precipitation of 1,205.1~1,656.8 mm, the recorded maximum being 1,682.2 mm (in 1933) and the minimum being 691.3 mm (in 1988). Affected by topography and monsoon air, rainfall has an uneven time and spatial distribution. From north to southeast, rainfall decreases. The period from April to September is the rainy season, and the rainfall in this period produced about 84.0% of the annual rainfall. The rainfall from June to July is 44.5% of the total, and the rainfall from October to next March is only 16.7% (Fig. 2).

Based on stratum lithology and hydrogeologic conditions, the groundwater in this area can be classified into three types: the carbonatite karst water, the bedrock fissure water, and the pore water in Quaternary loose deposit (Fig. 3).

The carbonatite karst water is mainly found in the limestone and dolomite layers of the Guanling Formation and the Yongningzhen Formation of Triassic, which is located at the outside edge of the main scarp of the Guanling rock avalanche. Generally, this kind of water is drained in the form of springs in the contact zone of its underlying Yelang Formation layer. There exists some obvious fluctuation in time of year and quantity of spring water; in particular, large springs can be formed during the rainy season.

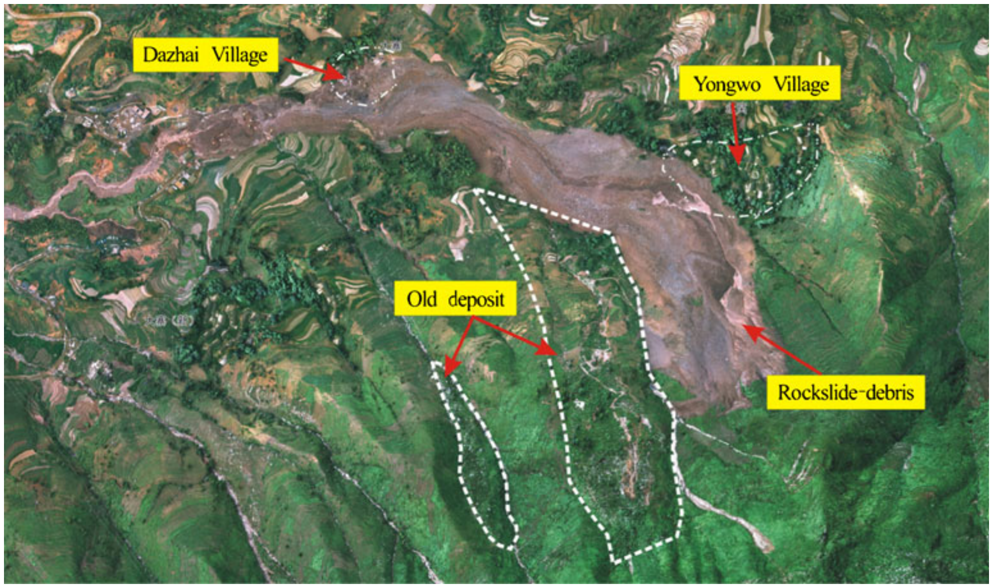


Fig. 1 Aero-image of rockslide-debris flow at Dazhai, Guanling, Guizhou

The bedrock fissure water is mainly found in the structural fractures and weathering fissures of the Yelang Formation fragmentary rock and the Emei Mountain basalt. There are many small-flow spring areas in the gully, and most of them are dry, with little water.

The pore water in Quaternary loose deposits is found primarily in the old rockfall deposits at the two sides of the valley, and during some seasons, springs are exposed within a thick layer, with a small rate of flow but extensive dynamic fluctuation.

Thus, a typical and complex groundwater system is formed in this area. Because of the evident fluctuation of groundwater, the variable regularity of spring flow and water level is consistent with that of atmospheric precipitation. Every year, the period from May to September is the high water flow period, but the period from January to March is the low water flow period. Spring flow in the former period is 5–10 times, even 100–200 times that of the latter. Therefore, the rainfall in the rainy season plays an important role in slope instability. Here, three zones are categorized from the head to the toe of the slope as follows:

- A recharge area at the top. Precipitation is the main source of groundwater in this area. Controlled by the watershed, the impervious layer and the geologic structure, a complex groundwater network is created, and groundwater enrichment zones are formed in this part. Also in this area, the precipitation water supplies the groundwater rapidly through the karststructural voids, the erosion fractures, sinkholes and funnels. The groundwater is closely related to the precipitation, given that it can flow freely through the geologic structures.
- A weak runoff and strong outflow region in the middle part. Due to the lithological difference, the runoff modes of groundwater are variable. In this area, the soft mudstone, shale and sandstone of Yelang Formation existed so that there was a transition from steep to gentle layer. At the contact zone between this area and the top carbonatite area, the karst water is discharged to the ground surface as large karst springs. Meanwhile, because the groundwater is often found in bed rock fissures and flows along the slope, a concentrated fissure seepage zone was formed.
- A weak outflow region at the toe. The lower strata are composed mainly of interbedded sandstone and shale, as well as coal seams of the Longtan Formation. As a result, this region is characterized by a water-resistant layer to some extent. And because of the relatively low activity of groundwater, the contact discharge zone is often formed in the transition zone of the stratum.

Deposit characteristics of the Guanling rock avalanche

Based on investigation and remote sensing, the Guanling rock avalanche could be divided into three parts: the source area of the

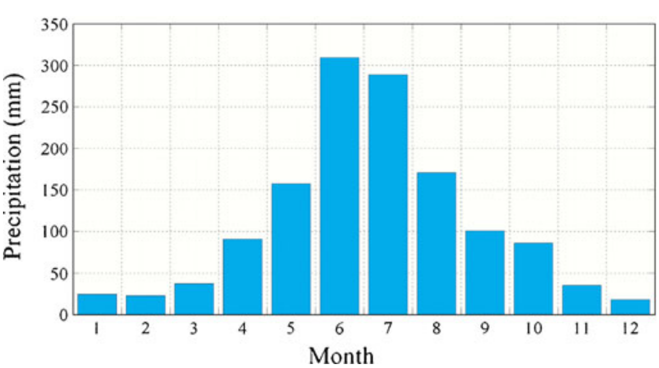


Fig. 2 Diagram of mean month precipitation at Guanling, Guizhou (1996–2005)

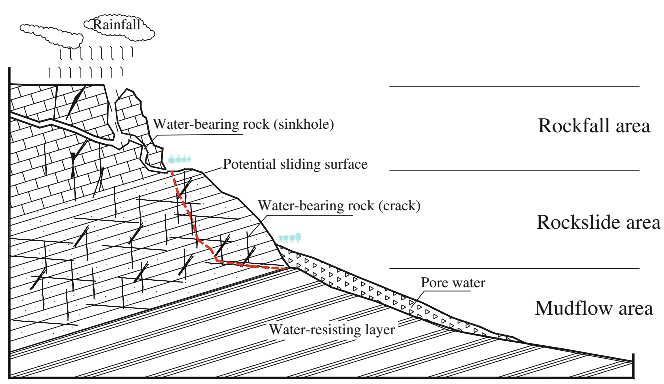
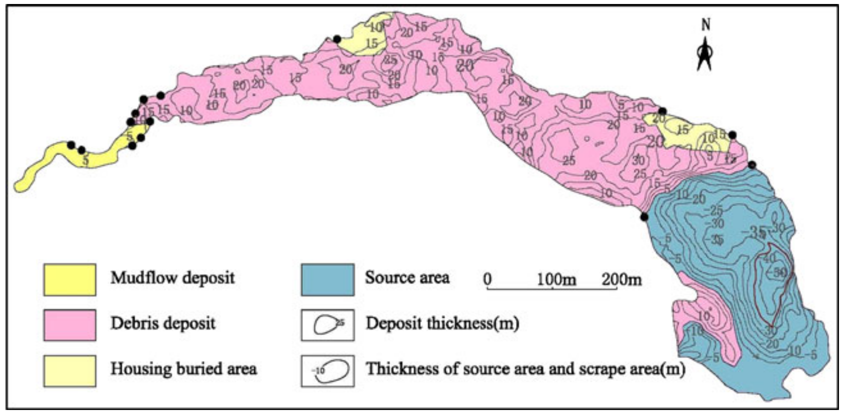


Fig. 3 Mountain structure and geo-hazard mode at Guanling region

Fig. 4 The deposit isopach map of rockslide-debris flow at Dazhai, Guanling, Guizhou



rockslide, the debris flow deposit area, and the mudflow deposit area. The contour map (Fig. 4) is obtained using a 1:10,000 digital elevation model map. The volume of rockslide in the source area is about 1.15 million cubic meters, spreading over an area of 72,500 m^2, and the resultant maximum decrease of the top elevation is 55 m. Due to the entrainment of surface residual soils and disintegration of rock mass, the volume of this rockslide-debris flow is 1.75 million cubic meters, the area is 114,000 m^2 with a maximum deposit thickness of 40 m. The elevation of the main scarp is about 1,180 m, the toe of the surface of rupture is 950 m in elevation, and the minimum elevation of the deposits at the frontal edge is 760 m.

- The source area: this area mainly consists of sandstone of the Yelang Formation, and the residual deposit is primarily composed of boulders, with a general diameter of tens of centimeters, and a maximum diameter of 1 m. The depth of the scrape zone is about 35 m, and the head scarp is steep, with a grade of 70–80° and a height difference of 55 m.
- The debris flow deposit area: this area mainly consists of cobbles and boulders, having an average diameter of several centimeters, and a maximum diameter of less than 50 cm. The deposit thickness is 5–20 m with a maximum of 30 m.
- The mudflow deposit area: this area is formed by the transportation of old residual soils and is mainly composed of clay soils, with a prominent layered structure caused by multi-period mudflows. The current mudflow deposit thickness is 5 m.

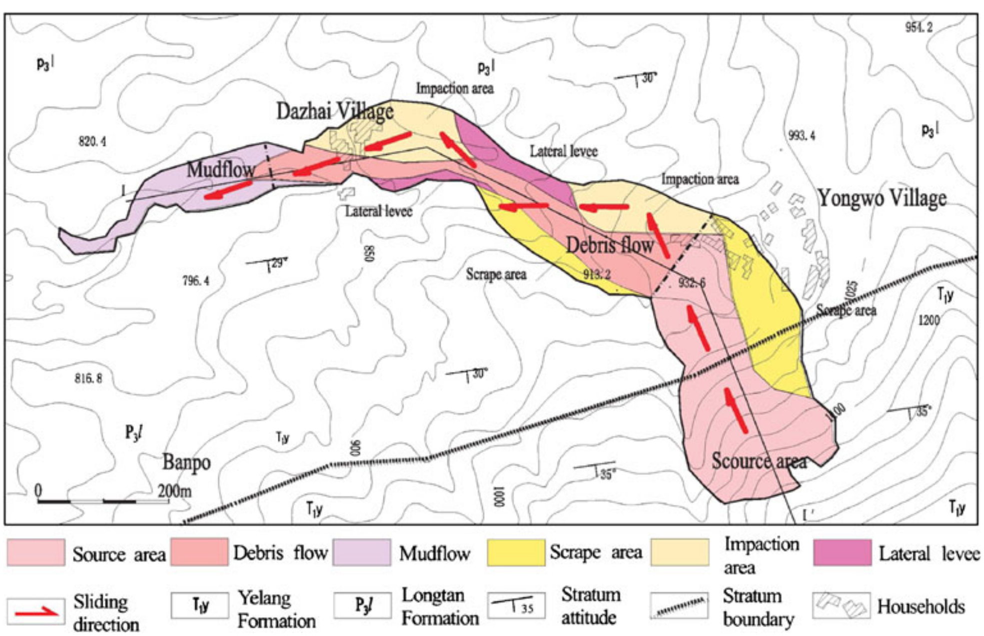
Dynamic characteristics of the Guanling avalanche

Field investigation and aerial images show that, the Guanling rock avalanche originated at an elevation of 950.0–1,180 m. The sliding direction of the source area is N 22° W, and the sliding distance is about 500 m. After impacting on the opposite side wall and destroying 21 households at Yongwo Village, the rock avalanche transformed into a debris flow along N 64° W, with a flow distance of about 800 m. At the front edge of the debris flow, the mudflows of historical periods were deposited, with a strike of N 80° W and a flow distance of 200 m (Figs. 5 and 6).

Dynamic zoning of the Guanling avalanche

The term “rock avalanche” has been used in the literature, as a simplification of the term complex “rock slide-debris avalanche,” proposed by Varnes (1978). Hungr et al. (2001) suggested that the term “rock avalanche” be reserved for flow-like movements of

Fig. 5 Map of rockslide-debris flow dynamic zoning at Dazhai, Guanling, Guizhou



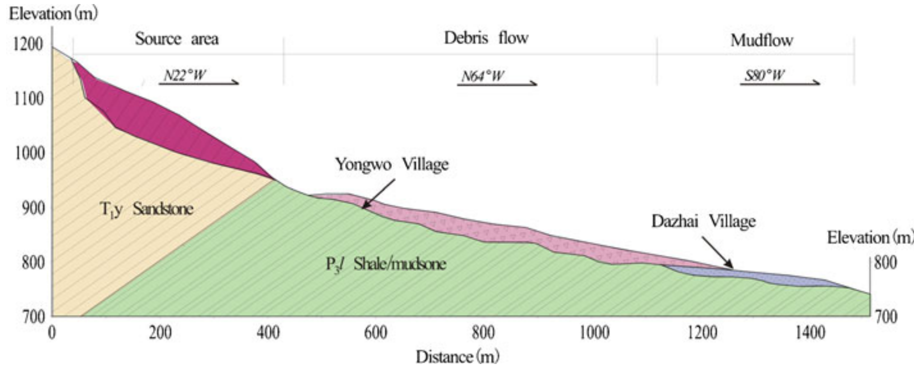


Fig. 6 Cross-sectional profile of rockslide-debris flow at Dazhai, Guanling, Guizhou

fragmented rock resulting from major, extremely rapid rock slides and recommended that the term "rock slide-debris avalanche" be used when a rock slide mobilizes a large quantity of debris by entrainment of liquefied substrate from the path.

The dynamic characteristic of the Dazhai rockslide is similar to that of the Wulong rockslide which occurred on June 5, 2009 in Chongqing, China (Yin 2010). It can be divided into the following three parts:

(1) The source area. The volume of the residual deposits in this area is about 0.35 million cubic meters. It can be seen from the original landform that, the source area was located at the transition zone of the upper steep carbonatite (with a grade of more than 80°) and the lower soft sandstone and shale of Longtan Formation (with a grade of about 15–25°), and with a terrain slope of 30–60°. The east and west side of the sliding masses are separated by valleys, and the east valley is shallow with a depth of 10 m, but the west is deep with a depth of 20–30 m. The sliding mass layer is the sandstone of Lower Triassic Yelang Formation (T_{1y}) and is a reverse slope with an attitude of N65–75°E/SE∠30–35°. High-angle joints are developed in the rock mass, and a set of steep joints with a dip angle of 65–75° compose the back edge separation surface. At the front edge, the Yelang Formation stratum is a discordant contact with the Longtan Formation, which forms a hard rock structure overlaying the soft (Fig. 7).

The main scarp has an elevation of about 1,180 m and the elevation of the toe of the surface of rupture is about 950 m indicating a height difference of up to 230 m. The width is about 150–200 m, and the thickness is about 50–70 m. The bottom interface is irregular, showing a composite feature of collapse and sliding. On June 29 when the authors conducted a field investigation, collapses occurred many times and the slide mass was still unstable, indicating complex destabilizing characteristics.

After destabilization, the sliding mass slid toward N 22° W and impacted the opposite cliff, and it then experienced run-up beginning in the valley (elevation 932 m) and rising to an elevation of 975 m, destroying 21 households at Yongwo Village. At the east of sliding mass, a scraped area with a length of 200 m and a width of 100 m was generated, which entrained the surface terraces and residual soils and increased the volume.

(2) The debris flow area. The deposit volume of this area is about 1.3 million cubic meters, with a general flow strike of N 64° W, a grade of about 25° and a flow distance of 650 m. After impaction on the opposite right sidewall of the valley, the sliding mass flowed about 150 m and covered the mudflow with

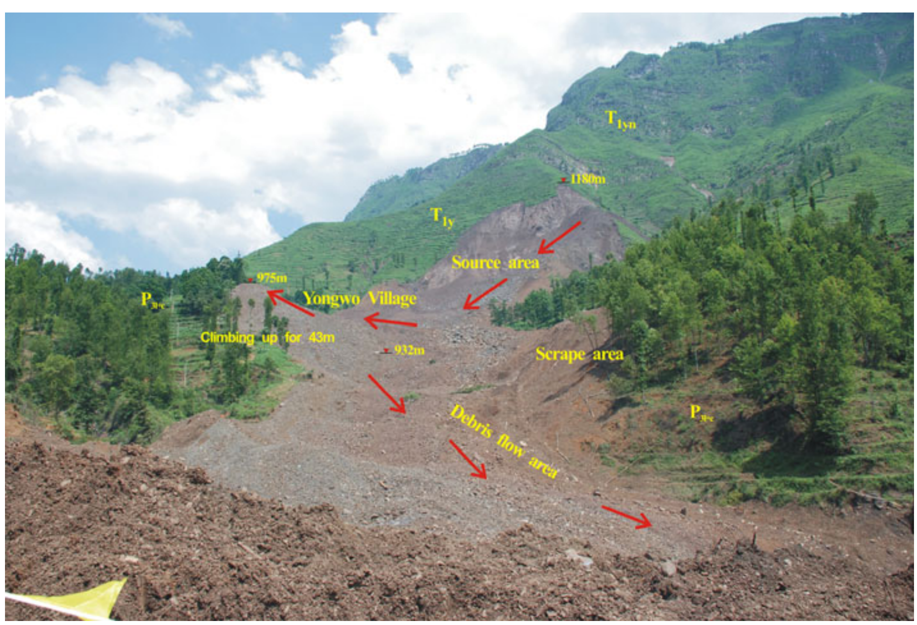


Fig. 7 The Dazhai rockslide moved upward and destroyed the Yongwo Village

(1) Scarping zone and lateral levee
(2) Multi-layers structure of the debris at the collision zone
(3) Pipeline multi-flows of the debris
(4) Lateral levee caused by the side pressure of debris

Fig. 8 Features of the flow and deposit structure of the debris, Dazhai

a deflection of S 80° W. The debris flow has the following characteristics (Fig. 8):

- Scrape characteristic. After impaction and destroying 21 households at Yongwo Village, the sliding mass experienced a deflection of movement. Part of the debris flowed westward and impacted the left levee of the valley and rose up about 20–30 m, scraping the soft Longtan Formation shale and the surface residual soils for a length of 250 m. The upper part of the deposit is mainly composed of crushed rocks, having a general diameter of tens of centimeters and the maximum of less than 1 m. The lower part mainly consists of clays (50% of total) and boulders with a general diameter of more than 1 m, indicating the means for the scraping action.
- Lateral pressure characteristic. As the impact of the boundary layer frictional resistance, the shear difference is increased between the debris flow located at the edge of the valley and that in the middle, which resulted in the slowing of flow velocity. Due to the increase of lateral pressures, debris at the edge stopped moving, producing a deposit thickness larger than that in the middle. There was also the formation of a lateral pressure levee, indicating a typical lateral pressure characteristic.

(a) Rock flow lobe over mudflow
(b) Front lobe consisted of clay mudflow

Fig. 9 Features of the front deposit structure of the mudflow, Dazhai

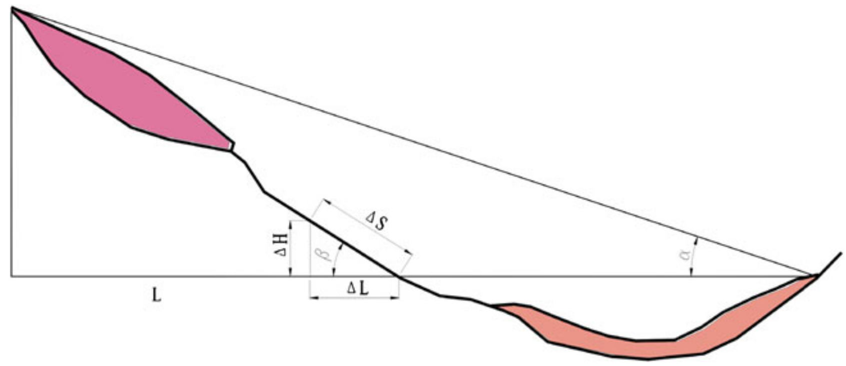


Fig. 10 Geometry of a landslide (Scheidegger 1973)

- Superimposed deposit characteristic. During the course of the flow downward under the action of inertia (due to the topographic relief), the debris flow transformed from the integral flow into the pipeline-like flow. Thus, the flow velocity decreased sharply and a prominent superimposed deposit characteristic appeared.
- Impaction characteristic. After flowing downward for about 600 m, the debris flow still had a high velocity. Because of the deflection at Dazhai Village and the decrease of the cross-sectional width from 150 to 80 m, the debris flow converged into concave gullies, destroying Dazhai Village.

(3) The mudflow area. This area has a volume of 0.1 million cubic meters, a thickness of 5 m, a width of 100 m, and a length of 200 m. The middle part of the valley is overlapped by the debris flow with a general thickness of 1 m and clays distributed at the two sides. The cobbles and boulders in this area had rounded features, which is different from that in the debris flow area. It indicates that the mudflow happened in the early stage of movement (Fig. 9a). Investigation shows that the lower part mainly consists of clays with a few cobbles and boulders. Because of high water content, a mudflow formed at the front edge (Fig. 9b).

Estimation of the slide velocity

Presently, the prevailing international formula for estimating the sliding velocity of large rockslide is as follows (Fig. 10; Scheidegger 1973):

$$V = \sqrt{2g(H - f \times L)} \qquad (1)$$

Where V is the gravitational acceleration; H is the height difference from the starting point to the estimating point; L is the horizontal distance from the starting point to the estimating point; f is the tangent of effective friction angle, which is the angle of a line from the avalanche starting point to the most distant end of the debris from the longest running avalanche.

Based on Fig. 10 and by using Eq. 1, the estimated velocity v when the slide mass reached Yongwo Village can be given:

$$V = \sqrt{2g(H - f \times L)} = \sqrt{2 \times 9.8 \times (205 - tg(19°) \times 580)} = 10.18(m/s) \qquad (2)$$

Accordingly, the estimated velocity at the toe of the surface of rupture is 44.84 m/s. When the slide mass reached the valley bottom, a peak estimated velocity is generated with the value of 45.24 m/s. Obstructed by the front furrow bank, the estimated velocity is decreased to 31.42 m/s at the lower part of Yongwo Village. After rising up for 43 m, the slide mass reached Yongwo Village and destroyed houses with an estimated velocity of 10.18 m/s (Table 1, Fig. 11).

Based on the geometrical relationship in Fig. 6, the effective friction angle is about 16°, so, the velocity when the slide mass reached Dazhai Village is estimated to be 10.76 m/s ($H = 350\,m, L = 1200\,m$).

It is worth noting that Eq. 1 put forward by Scheidegger could be over simplified. Because the dynamic characteristics at the debris flow stage is very complex and includes the scrape action, impaction, lateral frictional resistance, and base liquefaction, Eq. 1 may not be directly applicable to this case.

Formation conditions for rock avalanche

Field investigation shows that there are hundreds of thousands of cubic meters of old deposits accumulated in this area. The parent rock is a steep carbonatite layer located at the mountaintop. The Yelang Formation sandstone layer located at the middle part of

Table 1 Estimated velocity at the stage of sliding downward and climbing

Cross-section No.	Location	Dynamic state	H (m)	L (m)	α (°)	v (m/s)
1	Toe of surface of rupture	Sliding downward	230	370	19	44.84
2	Gully bottom	Sliding downward	258	446	19	45.24
3	Lower part of Yongwo Village	Climbing	227	513	19	31.42
4	Yongwo Village	Climbing	205	580	19	10.18

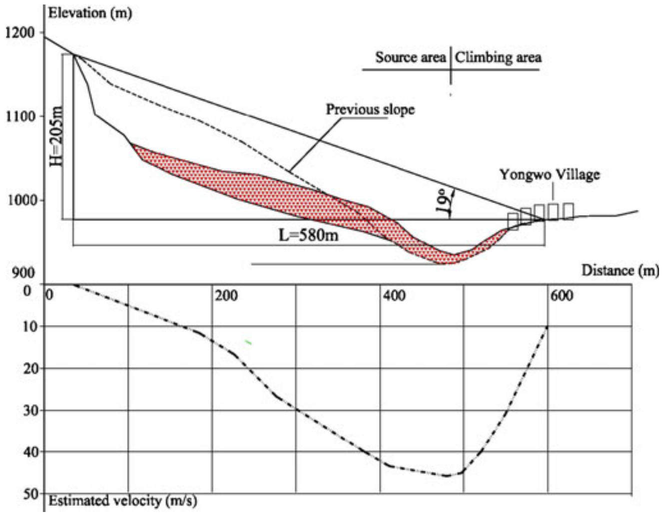


Fig. 11 Geometry of the Dazhai rockslide and velocity at the stage of sliding downward and climbing

the mountain is mainly composed of small collapses and rockslides, with small sliding distances. The type of composite rock avalanche with a sliding distance of 1.5 km is rare in Guizhou Province, China.

Geology and topography conditions

Evans (1984) has reported a special style of catastrophic bedrock slope instability similar to Guanling avalanche that develops in situations where a layer of hard caprock overlies weaker softer ductile rocks, such as tuffs, shales, or flysch sediments. This mode of instability may involve toppling and/or spreading of the subjacent weak layer and has catastrophic potential.

The geology in this area shows that the upper part is mainly composed of limestone and dolomite with multiple joints, cracks, and sinkholes and has a pipeline-like flow at the same elevation as the buried river. In the contact zone with the lower sandstone, the central outflow region occurs with abundant large springs. Because this area is steep with a grade of more than 70°, collapse often happens. The middle part mainly consists of soft sandstone, with a grade of 30~60°, and the rock mass is divided into blocks by joints. Due to the abundant supply of the upper karst water, the springs are exposed at the contact zone adjacent to the lower shale layer. Because of the high continuity of the joints, as well as the hydraulic pressure, the stability of the rock mass is poor. The shale and mudstone layer with occasional coal seams is located at the bottom. This layer results in low permeability of the rock mass. Such geological structure with hard resistant caprock overlaying weaker softer ductile rocks, coupled with the central outflow region at the contact zone, has a potential for catastrophic rock avalanches (see also in Fig. 3).

The topography in this area is shaped like a “boot.” The upper steep landform easily led to slope instability, and the wide middle and lower part provided kinematic conditions for long run-out. The elevation of the mountaintop is 1,500 m, and the bottom is 700 m, with a height difference of 800 m. Transformation of the larger potential energy into kinetic

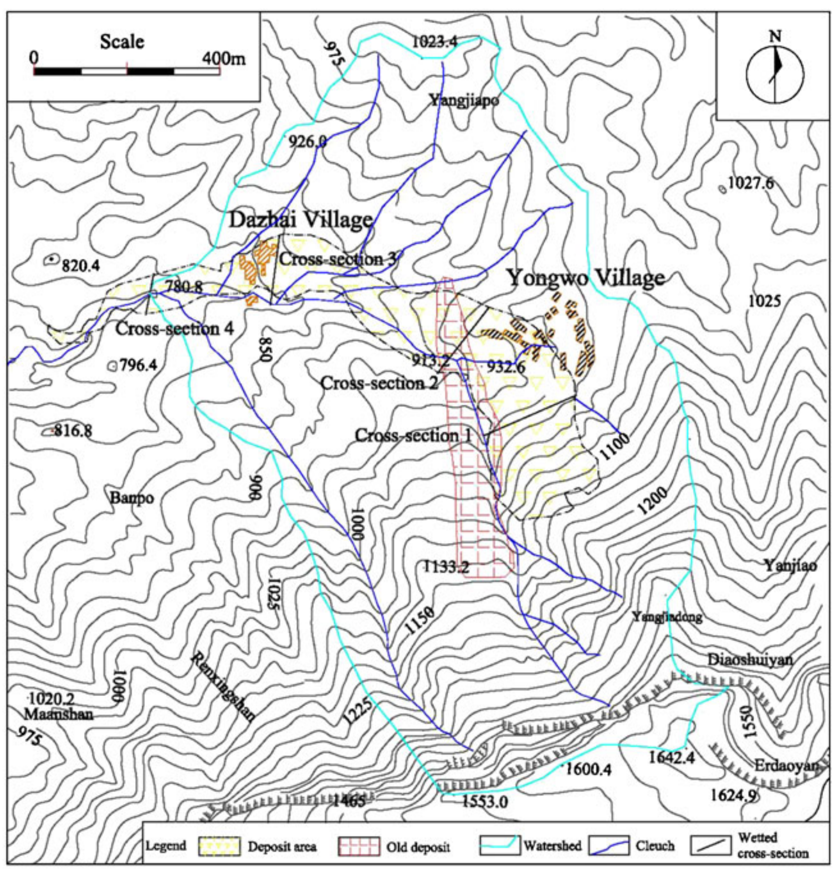


Fig. 12 Map of raining runoff zoning at the Dazhai rockslide-debris flow

Table 2 Parameters and runoff flow for four sections of the gully

Location	Bed length L (km)	Bed grade I (‰)	Affluxion time T (h)	Rainfall intensity Sp (mm/h)	Affluxion area F (km^2)	Loss parameter μ (mm/h)	Flow Qp (m^3/s)
Toe of surface of rupture	0.895	762.8	0.0262	12.92	0.44	27.88	5.35
Yongwo Village	1.11	599.7	0.0333	12.92	0.52	25.92	5.50
Dazhai Village	1.53	416.6	0.0476	12.92	0.94	20.01	8.89
Groove entrance	1.78	341.1	0.0570	12.92	1.22	17.85	10.79

energy made the occurrence of the rapid long run-out rock avalanche possible.

Rainfall and surface water runoff conditions

Dynamics of rapid landslides are adequately analyzed by the concept of sliding surface liquefaction in granular material, proposed by Sassa (2000). Once failure occurs and is followed by large displacement, the intense shearing within a thin shear band leads to a textural change within the material (grain crushing). But, due to the impact of a rockslide on the valley side and transformation to the debris with no clear shear zone, the liquefaction would transfer into fluidization, and a complicated process occurs that involves simultaneous entrainment, plowing, and lubrication at the front of a rock avalanche (Hungr 2006). When debris from a rock slope failure impacts channel or valley floor sediments, a destructive debris flow may be mobilized that travels well beyond the margins of the initial landslide debris (Evans et al. 2006). Similar effects may result from impacts of rockfall debris on saturated colluvium or talus forming the lower part of a valley side slope (Hungr 2006).

The local heavy rainfall is the primary trigger of the Guanling rock avalanche. According to the records of the local meteorological station, the accumulated rainfall in 24 h from June 27 to 28 is 310 mm, with an average intensity of 12.9 mm/h. The heaviest rainfall occurred from 5:00 to 12:00 A.M. on June 28, with an accumulated rainfall of 190.9 mm and an intensity of 27.1 mm/h. Rainfall affects the rock avalanche by the following two processes. First, the increased hydraulic pressure in joints and fissures of sandstone could have caused slope instability. Second, the valley runoff supplied a saturated base for the long run-out of the debris flow. Due to the absence of actual observation data, the flow is calculated by using an empirical equation recommended by the Institute of Highway Science, Ministry of Communications (1993):

$$Q_P = 0.278\left(\frac{S_P}{\tau^n} - \mu\right)F \tag{3}$$

where Q_p is the peak flow (cubic meters per second); S_p is the intensity (millimeters per hour); μ is the loss parameter (millimeters per hour); n is the rainfall decreasing index; τ is the confluence time (hour); F is the basin area (square kilometer).

Here, four typical cross sections are selected for study of the surface water runoff characteristics (Fig. 12, Table 2), and the flows are 5.35, 5.50, 8.89, and 10.79 m^3/s, respectively.

Figure 2 shows that the mean rainfall in June was 309 mm/month, i.e., 10 mm/day. If the maximum rainfall is 100 mm/day, then the flows of the abovementioned four cross sections will be 1.84, 1.9, 3.05, and 3.69 m^3/s, respectively. If the rainfall is 150 mm/day, the flows will be 2.7, 2.79, 4.48, and 5.42 m^3/s, respectively (Fig. 13).

The above analysis indicates that the runoff flow from June 27 to 28 is two times that of the usual rainfall (100–150 mm/day), which resulted in the obvious increase of flow distance and velocity of debris. At the same time, because of the increased flow, the old deposits (limestone blocks) at the rockslide toe could have been eroded, which might have contributed to the slope instability.

Conclusions

On June 28, 2010, a catastrophic rock avalanche was triggered by an abrupt rainstorm, resulting in 99 deaths. Based on our field investigation, we gathered a large amount of firsthand data for this rock avalanche and then analyzed the geological settings and weather, deposit characteristics, dynamic characteristics, and formation conditions. From the Guanling case, we concluded that the sudden storm

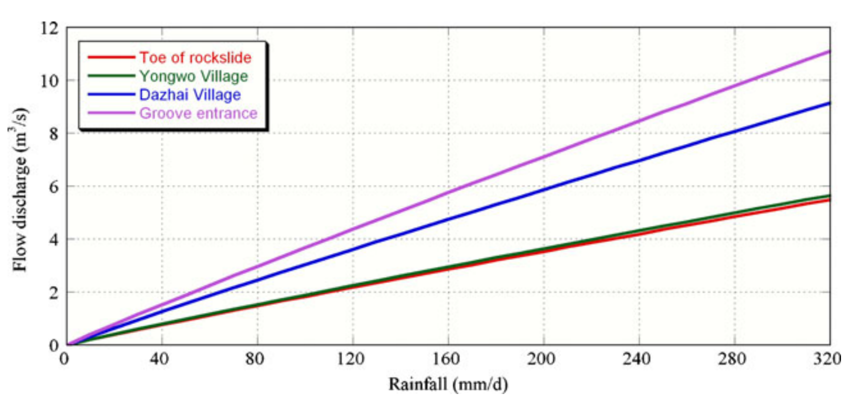


Fig. 13 Relationship between daily rainfall and flow of the gully of the Dazhai rockslide-debris flow

was the main trigger, and the unique topography played an important role for the movement characteristics of the rock avalanche. In fact, the mechanism of this kind of rock avalanche is very complex, especially for the failure prediction and the timing and reliability of the disaster prediction. As in this case, many rapid rock avalanches have such unique characteristics such as quick onset, subtle characteristics, and complex kinematics. It is difficult for precise prediction and disaster prevention. Therefore, mitigation of such disasters requires great diligence with preventive safety measures such as early warning and rapid evacuation for the affected communities.

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