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Recent catastrophic landslides and mitigation in China

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Abstract: Increasing population density and development of mountainous terrain have brought human settlements within reach of landslide hazards. In recent years, due to the shortening of return period for severe natural events such as heavy rainfall, snowline retreating, great earthquake together with human activities, catastrophic landslides happened more frequently than before, resulting in large-scale casualties due to the increasing occurrences of rapid long-runout rock avalanches, especially in China. This paper presents some typical case histories related to the catastrophic landslides, including the Guanling rock avalanche, the Yigong rockslide-debris avalanche, the Wenchuan earthquake-induced landslides and the Danba landslide. They occurred in the last decade. Moreover, taking the Jiweishan catastrophic rockslide-fragment flow and the Yuhuangge landslide located in the new Wushan Town for examples, early-warning system and risk management on landslides are discussed in detail.

Key words: catastrophic landslides; rainfall; snowline retreating; earthquake; human activities; mitigation

1 Introduction

Recently, numerous landslide disasters occurred due to the increasing population density and development of mountainous terrain. Perhaps the most serious threat arises from small, high-frequency landslides such as debris flows and debris avalanches. Large and relatively low frequency rock avalanches also contribute to a significant hazard due to their immense capacity for destruction assessment of rapid long-runout events. It is a significant and crucial problem to be solved [1].

Studies show that in recent years, rapid and long-traveling catastrophic landslides happened greatly for the shortening of return periods for severe weather events such as heavy rainfall and snowline retreating, as well as for the occurrence of great earthquake and human activities, especially in China [2–7]. For example, thousands of landslides were triggered by the devastating Wenchuan earthquake. They caused great casualties and property loss.

As for the studies on catastrophic rockslide, lots of achievements have been gained. But in fact, the dynamic mechanism of such geohazards often includes more than one important factor. So it is very difficult to explain or describe the whole dynamic process from its start-up to stop only with any one of the factors.

Based on the current researches and engineering examples, the author presents some cases related to catastrophic landslides. The main types include: (1) rainfall-induced landslide; (2) snowline retreating-induced landslide; (3) earthquake-triggered landslide; and (4) human activity-induced landslide. In addition, a failure case study and a successful one on early-warning and mitigation are discussed.

2 Rainfall-induced landslide

On June 28, 2010, a catastrophic rock avalanche occurred after an extreme rainstorm at Guanling, Guizhou, China (Fig.1). This rock avalanche has a long-runout distance of 1.5 km and a debris volume of 1.75×10^6 m^3. It instantly buried two villages and resulted in a death toll of 99.

Guanling rockslide-debris flow was originated in the coal strata. Its upper part was limestone and dolomite. Its middle part was sandstone with gentle inclination. Its lower part was shale and mudstone and locally coal seam (Fig.2). This kind of unique geological structure, with hard resistant caprock overlying softer ductile rocks, coupled with the central outflow region at the

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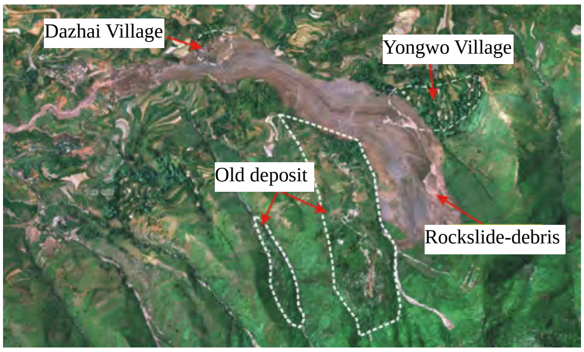


Fig.1 Aero-image of Guanling rockslide-debris flow.

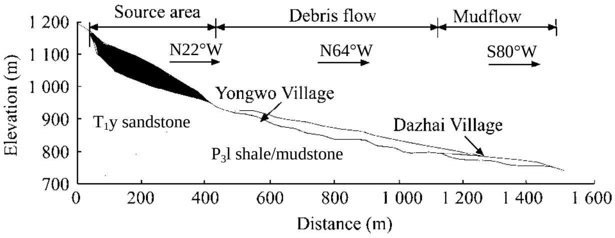


Fig.2 Profile of Guanling rockslide-debris flow.

contact zone, has the catastrophic potential for rock avalanches and creates challenges for engineering geological/hydrogeological analyses.

The topography showed that the hillside slopes were steep at the upper portion but gentle at the lower portion, with the shape of a “boot”. The upper steep landform could easily lead to the slope instability due to its high static shear stresses, and the wide middle and lower parts provided the kinematic conditions for long-runout of debris flow. Transformation of large potential energy to kinetic energy contributed to the formation of a rapid long-runout rock avalanche.

Based on the stratum lithology and hydrogeological 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 the Quaternary loose deposit (Fig.3).

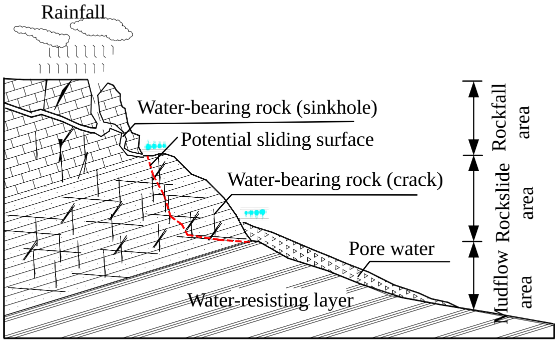


Fig.3 Geological structure and geohazard modes at Guanling region.

The rainfall from June 27 to 28, 2010, was the apparent triggering factor of this catastrophic avalanche. The measured rainfall more than 310 mm within 24 hours hit the local historical records over the last 60 years. The pore water pressure in the discontinuities of sandstone had a significant effect on the slope stability. The valley runoff supplied a saturated base for the long-runout debris, inducing an additional increase in the terminus distance and the velocity of the avalanche movement.

From the investigation, we concluded that the sudden storm was the main triggering factor and the unique topography played an important role in 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, etc., it is difficult to precisely predict and prevent disasters.

3 Snowline retreating-induced landslide

On April 9, 2000, a gigantic rockslide-debris avalanche occurred at the Yigong River in Bomi County, Tibet [8]. The avalanche took about 10 minutes to travel a horizontal distance of 10 km through a vertical elevation difference of 3 330 m from its source at 5 300 m to the lobe at 2 190 m (Figs.4 and 5).

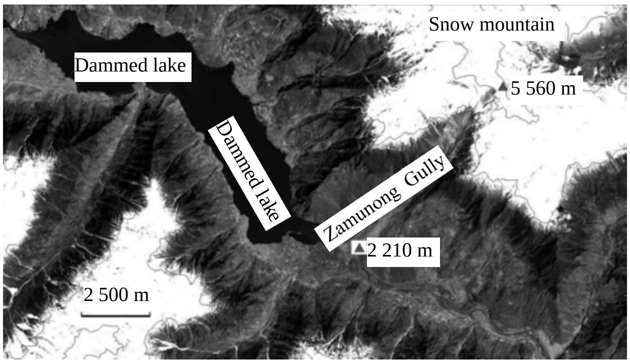


Fig.4 Remote sensing image of Yigong rockslide-debris avalanche (10 km runout distance).

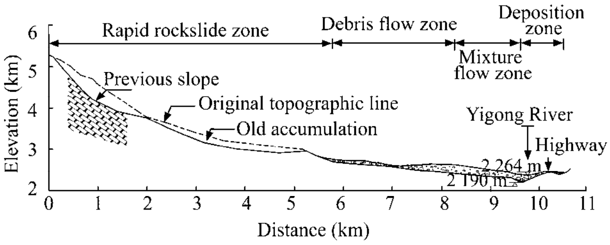


Fig.5 Cross-section of Yigong rockslide-debris avalanche.

The avalanche dammed the Yigong River and created a large dammed lake. The geometry of avalanche deposit was about 2 500 m long, 2 500 m wide and 60 m thick in average, covering an area about 5 km^2 and a volume of about (280–300) × 10^6 m^3 (Fig.6).

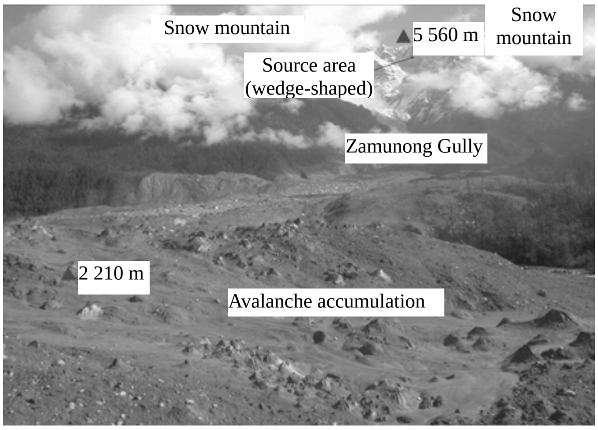


Fig.6 Photo of Yigong rockslide-debris avalanche.

As a result of snowline retreating, the wedge-shaped rockslide initiated as a large water-saturated rock mass of over 10 × 10^6 m^3 at an approximate elevation of 5 520 m at the Zamunong Gully, a branch of the Yigong River.

Through aerodynamics, the wind tunnel test model was applied to determining the aerodynamic parameters from the initial rockslide-fall stages along the wedge-shaped bedrock shear outlet to the first collision with lateral sides as the integrity mass of the avalanche. The effect of air-cushion was predominant. The numerical analysis was also used to establish the flying motion equation of the mass on the basis of wind tunnel test results. The results inferred that the Yigong rapid rockslide-debris avalanche flowed in the air for about 12.9 s from leaving the shear outlet to colliding with the floor of Zamunong Gully with a horizontal sliding distance of 1 050 m and a vertical dropping distance of 530 m. The elevation of the colliding point was about 3 317 m, and the velocity of the avalanche mass detaching from the shear outlet was around 81.8 m/s, and the collision velocity was around 117 m/s. The study indicated that the avalanche mass with air-cushion effect had a longer flying time and a longer flying distance than the one without air-cushion effect.

4 Earthquake-triggered landslide

The Wenchuan earthquake (M_s = 8.0; the epicenter at 31.0°N, 103.4°E; and the focal depth was 14.0 km) was triggered by the reactivation of the Longmenshan fault in Wenchuan County, Sichuan Province, China, on May 12, 2008. The Longmenshan tectonic belt includes a series of tight folds with a NE strike and an echelon fault system composed of three main sub-faults. This earthquake directly caused more than 15 000 geohazards in the forms of landslide, rockfall and debris flow, which resulted in a death toll of about 20 000. It also caused more than 10 000 potential geohazard points, especially the rockfall, reflecting great differences on high and steep slopes in mountainous areas caused by the earthquake. Obvious amplification effect of seismic force has been observed on the top of mountains. That is to say, the seismic force will be magnified on the peak.

Studies showed that the Niujuangou Sturzstorm, the Chengxi landslide and the Donghekou landslide-debris flow had the characteristics of air-cushion lubrication but were difficult to be analyzed using the sliding zone liquefaction theory. The landslides or landslide-debris flows were located along the Wenchuan earthquake ground fracture zone, where the peak earthquake acceleration exceeds 1.5*g* and long and strong shocks were transmitted to the upper surfaces of the rock mass, so that they experienced horizontal movement and vertical uplift [2].

Using the flight aerodynamic characteristics analysis method and wind tunnel test, Xing et al. [9] studied the sliding characteristics of rapid landslides over a short distance. It was concluded that the wing effect of aircraft would be generated during the sliding of rapid landslides, which not only made the landslide travel further, but also converted more potential energies into kinetic energy. So, it would move with a greater velocity. In general, this kind of aerodynamic force could increase the sliding distance by one third.

The reach of the Donghekou landslide at the sliding stage was also simulated under the aerodynamic state by Xing et al. [9] (Fig.7).

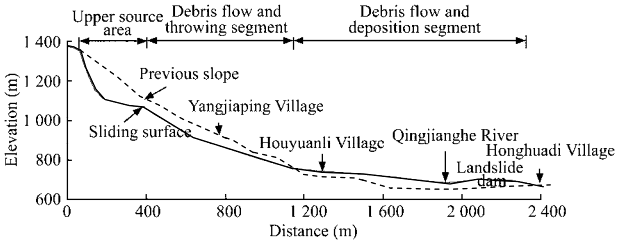


Fig.7 Cross-section of Donghekou landslide-debris flow triggered by Wenchuan earthquake, Qingchuan County [9].

The results showed that the reach under the aerodynamic was nearly increased by 50% under the normal state (i.e. no air-cushion effect) (Fig.8). Thus, the total runout under air-cushion effect was increased by one third compared to the conventional estimation under the normal state.

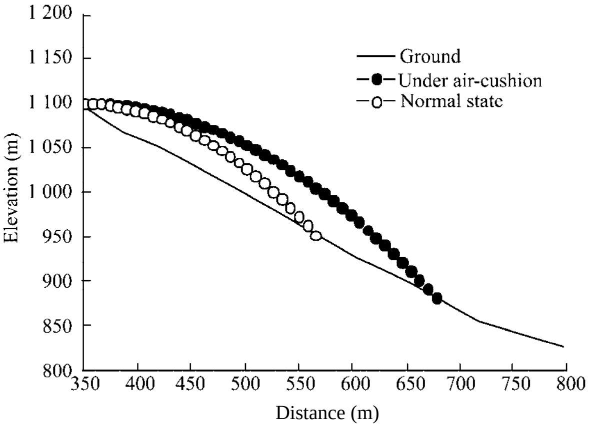


Fig.8 Comparison of reach at Donghekou landslide between aerodynamic method and normal method.

5 Human activity-induced landslides

Due to the rapid expansion of cities and towns in China, many regions near or at ancient landslide sites have been used and are being selected as the sites of construction in the mountainous areas. The researchers and engineers are facing a big challenge to ensure safe utilization of old landslide sites as construction sites on the base of control.

The Danba site has an ancient landslide on the Dadu River (Fig.9). The new town was constructed on the debris of the ancient landslide and now has expanded rapidly to the slope. The ancient landslide was reactivated due to the irrational slope cutting (Fig.10).

Fig.9 Danba New Town located on the ancient landslide (2003).

Fig.10 Reactivated landslide due to irrational slope cutting (2003).

In July 2003, a 28 m high slope that was improperly supported was cut in the front of the ancient landslide. The cutting triggered the reactivation of the ancient landslide with a volume of 2.5 × 10^6 m^3. Its maximum displacement velocity was greater than 50 mm per day. The new town would be totally destroyed by the landslide if no stabilizing measure was adopted.

Therefore, an emergent measure was adopted (Fig.11): sandbags with a volume of 4 000 m^3 were added at the foot in front of slope. Then the displacement was obviously dropped to 5 mm per day (Fig.12), which indicated that the sliding was effectively controlled. Meanwhile, 5 rows of prestressed anchors with a grade of 1 300 kN were arranged in the landslide to enhance the stability of landslide.

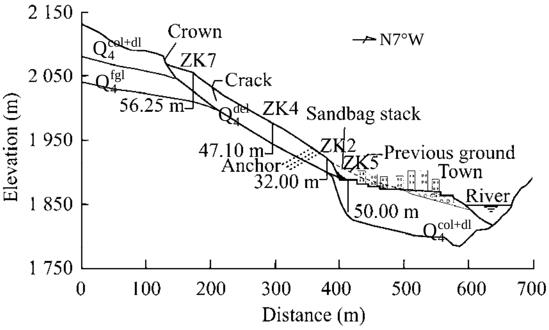


Fig.11 Corss-section of Danba landslide and layout of emergency work.

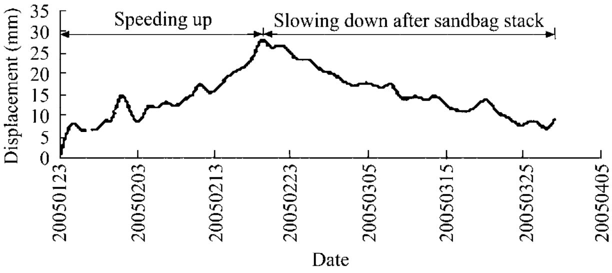


Fig.12 Time-history of displacement at Danba landslide (before and after sandbag stack on the toe).

Meanwhile, the simulation with FLAC^{3D} was conducted for the factor of safety (FOS) of the landslide under the conditions of nature, cutting, overloading in the front and anchorage with the strength reduction (SR) method.

The results showed that the SR method for FOS calculation had a good performance with an error of 0.1%–4.1% compared to those of generalized Janbu method, Morgenstern-Price method and Sarma method. However, the results for sliding zone analysis had a great error. The conventional methods for landslide stability analysis had considerable errors for landslide with soil-rock mixture, which would give unreasonable parameters for residual shear strength and friction movement of sliding zone. The value of internal friction angle, 29° instead of 24°–27°, was recommended for soil-rock mixture. In practice, internal friction angle obtained by the back analysis would be 20%–30% greater than the one obtained by the residual shear strength test. It should be also considered for the effect of landslide structure on the stability.

6 Early-warning prediction and mitigation

6.1 Jiweishan Mountain rockslide—a case history with early-warning system

On June 5, 2009, a huge catastrophic rockslide-fragment flow took place under a mass up to 60 m in thickness at the crest of the Jiweishan Mountain in Wulong County, Chongqing, China, with a long-runout distance of 1 500 m (Fig.13). The debris with a volume of over 7 × 10^6 m^3 moved towards the valley, and disintegrated and covered an area of 0.47 km^2. An iron-ore mine was obliterated, with a loss of 74 lives [10]. This catastrophic slide occurred in a sequence of coal measure strata. The sole factor responsible for the catastrophic behavior was the apparent bedding orientation.

Such massive rock slopes with oblique inclined thick bedding structures are widely distributed in the southwestern carbonate rock areas of China [11]. The failure pattern is conventionally recognized as lateral fall or toppling with a short-runout distance. Due to the existence of a front barrier of stable bedrock, the rock mass usually laterally fell or toppled first and subsequently accumulated on the lower gentler slope, and then would convert into a rockfall-accumulation of secondary landslide induced by overload, rainfall or other factors (Fig.14). The Jiweishan Mountain area had also been recognized as a high risky rockfall zone since 1994. Many mitigation measures had been taken to reduce the rockfall hazards. These measures included the establishment of an early-warning

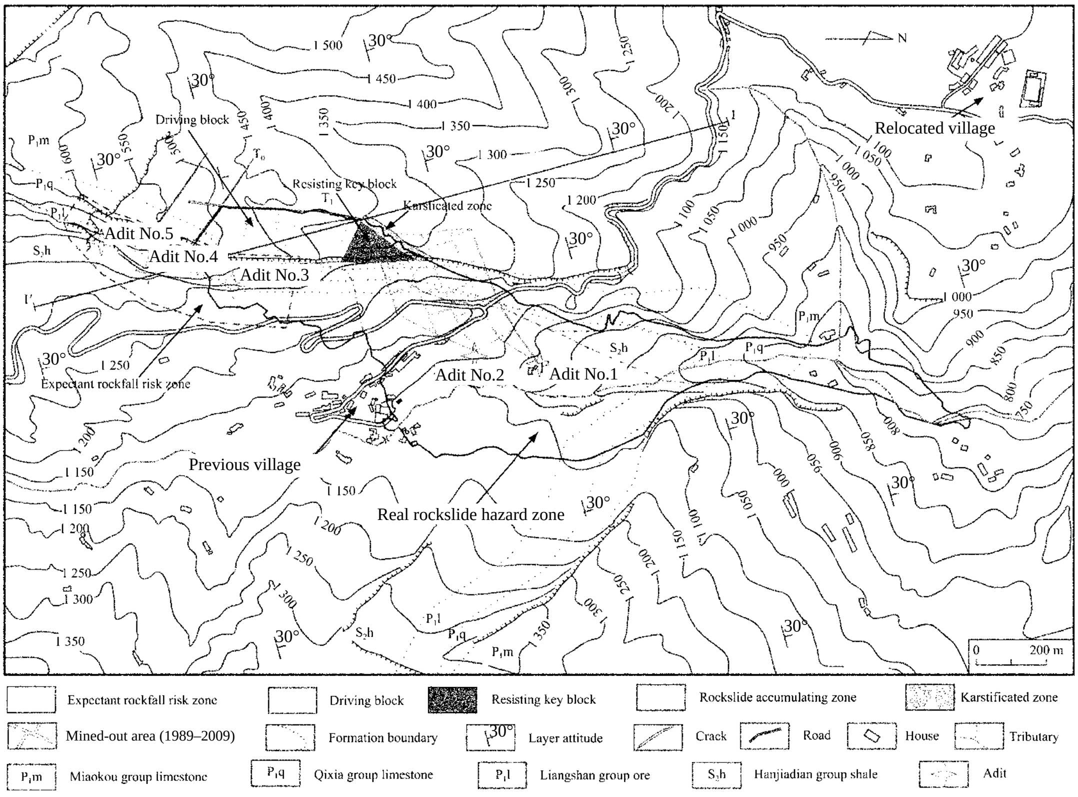


Fig.13 Layout of expected rockfall and real-happened rockslide-rock avalanche (fragment flow) (unit: m).

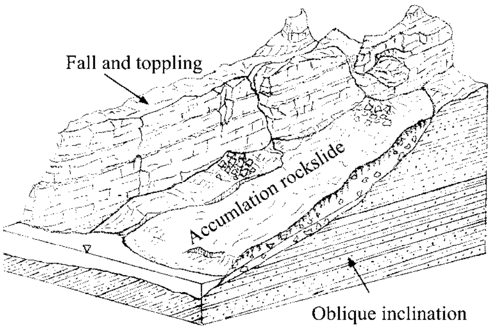


Fig.14 Schematic diagram of obliquely inclined bedding slope.

monitoring system. The relocation of the village of 300 residents started in 2005. The road within the risk zone was closed for several days before the occurrence of the rockslide, avoiding an estimated 1 000 injuries or deaths.

Unfortunately, the risk zone prepared by the local government did not allow for such a large catastrophic rockslide-fragment flow. The disaster on this size was not expected to occur. In assessing the means for mitigating geohazard for the Jiweishan Village, there were four deviations from the planned scenario: (1) the failure pattern was not a rockfall, but a rockslide-fragment flow with a long-runout; (2) the sliding direction did not accord with the predicted one, but progressed in a NNE-NW direction; (3) the volume was not 0.2×10^6 m^3, but actually 7×10^6 m^3; and (4) as for the runout distance, it was not the predicted one (100 m), but longer (1 500 m) (Table 1).

Table 1 Comparison of the actual results with expected ones.

Failure mode		Runout (m)		Sliding direction		Volume (10^6 m^3)	
Expected	Actual	Expected	Actual	Expected	Actual	Expected	Actual
Rockfall	Rockslide	100	1 500	East	North	0.2	7

The instantaneous failure of the smaller front rock mass was the main reason that a rapid-moving rockslide was subsequently triggered. Many scholars had studied the stability of thick bedded rock masses in view of a primary, or "key block". For example, Hoek and Bray [12] put forth the concept of "keystone" and emphasized its controlling role in the stability of total rock mass. Shi [13] presented a mathematical criterion for the stability of a key block by combining set theory and rock mass structure. Yin et al. [14] proposed the ideas and methods for stabilization of the key block.

The typical structure pattern of slopes was studied in the Three Gorges area of China [15]. The slopes were made of so-called "coal measure strata". The thick-bedded limestone with intercalations of 6 types of carbon or argillaceous shale was cut with two sets of near-orthogonal vertical joints and a set of soft material layered into huge blocks like "toy bricks" with a volume of several to 10^4 m^3. The thickness of the shale soft layer intercalations varied from 10 to 30 cm. Beneath this was a shale stratum containing coal, iron ore or bauxite with about ten or more meters in thickness that had been often excavated in the course of hundreds of years of mining (Fig.15).

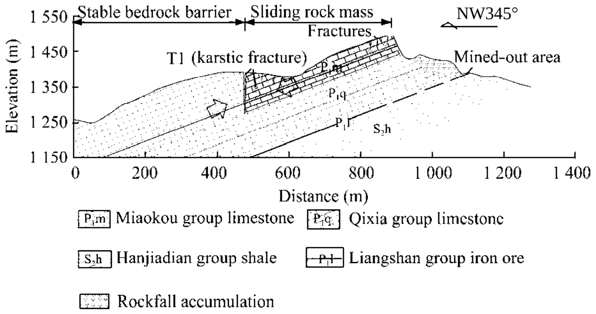


Fig.15 Profile of the relationship between the creep of the sliding rock mass and the barrier of dipping stable bedrock along the true dip direction.

As for the Jiweishan Mountain, a new failure pattern for inclined thick bedding rockslide-fragment flow is studied and introduced here (Fig.16), by analyzing the geological structure and the destabilizing iron ore excavation factor.

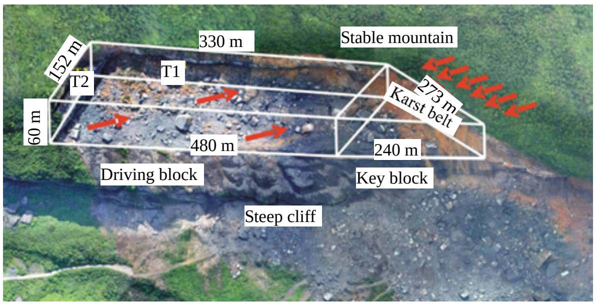


Fig.16 Geological model for the sliding mass of Jiweishan rockslide (before failure).

Based on the above analysis, it could be concluded that the failure mechanism of the apparent dip sliding of the Jiweishan Mountain rockslide is as follows: (1) the thick-bedded limestone is split into "toy bricks" by two sets of joints and the bedding composed of carbon soft-layers; (2) the sliding force of the driving block is gradually increased while the shear strength decreases due to the inclined rock mass, which creeps towards a true dip of NNW; (3) due to the barrier of stable bedrock, the driving block deflects into an apparent dip of NNE and destabilizes the northern supporting rock mass, which is the resisting key block; and (4) the key block fails instantaneously for the reasons of the increase in shear stress from the driving block and the reduction in strength and stiffness of the key block under the long-term karstic processes and mining disturbance.

The failure pattern was then simulated by using FLAC^{3D}. The result reveals that it is important to model the triggering mechanism of the instantaneous failure of the rock mass, and to model the physical properties, showing that the sliding force is increased by the driving rock mass and the fact that the strength of the key block is decreased.

As a result of the knowledge gained through field analysis and modeling for this rockfall, a possible early-warning prediction system is one option for hazard mitigation. As there is already a risk analysis for the area, the possibility that it could be revised to reflect the new information is suggested. Also, the option of stabilizing the key block through engineering methods must be considered by local government and/or community decision-makers.

6.2 Real-time monitoring—a successful case study on early-warning prediction

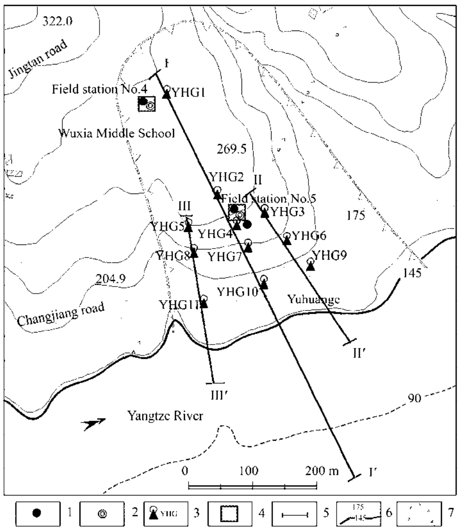
There were over 4 200 landslides distributed in the Three Gorges reservoir area of Central China. The monitoring has become an important way for avoiding potential casualties due to a sudden failure of landslides. Since 1999, a special monitoring and early-warning prediction system has been gradually established and improved. The system combines community-based monitoring with professional technology and covers 3 200 landslides, i.e. about 75% in total, in the whole reservoir area.

Many landslides have been regularly monitored with instruments that show an obvious deformation due to water level fluctuation [16]. There are dense population centered in the reservoir area. Geohazard can be triggered by a water level fluctuation between 145 and 175 m in elevation during reservoir operation. The regular monitoring could not be suitable for the early-warning prediction of landslides. It is necessary to develop a real-time monitoring system for landslides.

Since 2003, the author has carried out a real-time monitoring and early-warning prediction project for landslides at the relocated Wushan Town in the Three Gorges reservoir area. The monitoring station includes GPS with high-accuracy double-frequency to monitor ground displacement, time-domain reflection (TDR) technology, immobile borehole, inclinometer to monitor deep displacement, and piezometer to monitor pore water pressure, precipitation and reservoir water level.

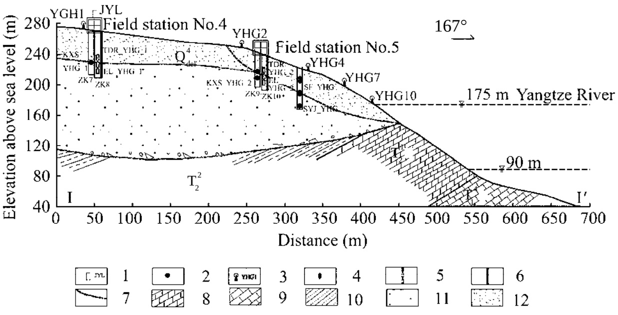
Wushan Town, about 100 km away from the dam site, is located at the entrance of the Wuxia Gorge, one of the Three Gorges. It is one of the 20 major relocated towns in the reservoir area. There are over 27 large-scale landslides in and around the new town. The Yuhuangge landslide is the largest one, on which hundreds of buildings and structures have already been relocated and reconstructed (Figs.17 and 18).

Fig.17 Overview of Yuhuangge landslide and densely relocated buildings.



1—Pore water pressure borehole; 2—Deep displacement borehole; 3—Ground displacement benchmark; 4—Field station; 5—Profile and No.; 6—Reservoir water level line; 7—Landslide boundary

(a) Layout of monitoring system location (unit: m).



1—Precipitation; 2—Pore water pressure; 3—GPS; 4—Water content; 5—Deep displacement; 6—TDR; 7—Sliding plane and failure surface; 8—T21 argillaceous limestone; 9—T14 limestone; 10—T22 purple-red mudstone; 11—Yuhuangge landslide; 12—Sub-sliding mass

(b) Profile of monitoring system location.

Fig.18 Maps of monitoring system at Yuhuangge landslide.

Compared with traditional methods, the real-time monitoring is continuous and traceable in the acquisition process, and the cycle of data acquisition is very short, usually within hours, minutes or even shorter. Based on the landslide monitoring experiences at the Three Gorges reservoir area, the early-warning prediction criterion for landslide is established. The critical situation is classified into four levels: blue, yellow, orange and red, representing no, slight, moderate and high risk level, respectively.

Deep displacement monitoring data recorded between May 2004 and September 2005 showed a cumulative displacement of 1.60 mm, 0.1 mm per month on average (Fig.19). It showed that the displacement was not significant and the slope was stable. However, during the period from September 2005 to February 2006, the displacement rate increased rapidly by almost 5 mm in a short period of time (around six months), and remained constant until December 2008. It was ten times more than the deformation rate recorded previously. The deep displacement direction of the landslide was definitively southeast (the same as the slope dip direction). The slope was stable in the mid February 2006. The deformation could be caused by internal adjustments within the landslide due to water level fluctuation. In a global sense, the landslide stability did not change. It remained in the creep sliding deformation stage. Because the deformation rate did not change, its early-warning prediction status remained at the same level, i.e. I-level (blue).

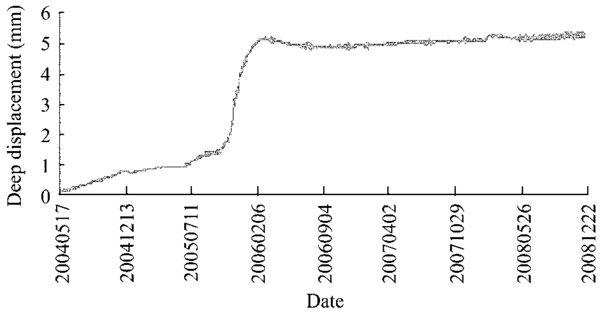


Fig.19 Time-history of displacement along the sliding surface (28.6–31.0 m in depth) at Yuhuangge landslide.

The allowed maximum water level of the Three Gorges reservoir reached 175 m above sea level in October 2008. Monitoring data in Fig.20 showed that the water level was 170.50 m above sea level on October 25, 2008. The reservoir reached the highest level of 170.64 m above sea level on November 23, 2008 and subsequently fell to the lowest level of 170.36 m above sea level on December 20, 2008. Landslide pore water pressure correspondingly changed from 71.49 kPa on October 25, 2008 to 72.77 kPa on November 23, 2008 and then 70.11 kPa on December 20, 2008. The variation in the pore water pressure indicated that the landslide structure was somewhat loose and there was a good hydraulic conductivity between groundwater and surface water. When the water level declined from 175 to 145 m, a high seepage pressure was formed whereas the pore water pressure increased when the reservoir water level was raised. Slope failure problems were not foreseen since protective works had been conducted. The water level variation in the reservoir had been considered for the stability analysis of the landslides and adjacent slopes.

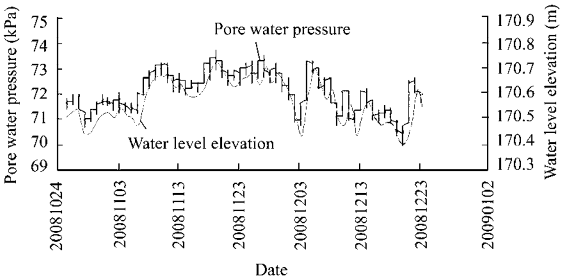


Fig.20 Monitoring curves of pore water pressure and water level elevation at Yuhuangge landslide.

The Brilliouin optical time domain reflectometer (BOTDR) is a newly developed innovative measuring technique, which utilizes Brilliouin spectroscopy and optical time domain reflectometer to measure strain generated in optical fibers as they are distributed in the longitudinal direction. Because of the BOTDR distinctive characters, it has been paid more and more attentions to and applied to monitoring system of various infrastructure engineering projects, such as tunnels, river embankments and landslides. The BOTDR technology was adopted in the monitoring of landslides at the Wushan New Town. The Yuhuangge landslide was under monitoring between August 2004 and September 2005. Data showed abnormally high strain at the points with elevations of 290 and 460 m. The two abnormal points were symmetric with a central point at 425 m (terminal point of the monitoring line layout), which indicated that the deformation occurred at the same place since the optical fiber was laid with the double lines. Strain reached 1 500 με and increased at a rate of 115.4 με per month.

It is concluded from the above analysis that the monitoring technique used in this demonstration project can be further applied to the monitoring of the other 3 200 landslides in the entire Three Gorges reservoir area.

7 Conclusions

In this paper, some typical case histories related to catastrophic landslides, including the Guanling rock avalanche, the Yigong rockslide-debris avalanche, the Wenchuan earthquake-induced landslides and the Danba landslides are discussed. The early-warning prediction and risk management on landslides are analyzed for Jiweishan catastrophic rockslide-fragment flow and Yuhuangge landslide located in the Wushan New Town.

Many case studies related to the catastrophic landslides indicate that these geohazards are of primary concern due to the large volume of displaced material and the resultant catastrophic impacts on the landscape and socioeconomic structure.

In fact, the mechanism of the rock avalanche is very complex, especially for the failure prediction and the timing and reliability of the disaster prediction. As discussed in this paper, many catastrophic landslides have such unique characteristics as quick onset, subtle characteristics and complex kinematics, complicated initiation mechanisms, etc.. It is difficult to give precise prediction and consequently to conduct effect disaster mitigation.

Therefore, the investigation and prevention of such disasters must be performed intensively, especially for the determination of factors of safety for house site, the establishment of rapid warning system and systematic evacuation program, which finally might contribute to the reduction of damages and casualties.

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